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DEFORMED GLACIAL DEPOSITS OF
PASSAMAQUODDY BAY AREA,
NEW BRUNSWICK:
PRODUCTS OF SEISMIC SHAKING?

by

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Research report



**DEFORMED GLACIAL DEPOSITS OF PASSAMAQUODDY BAY AREA,
NEW BRUNSWICK: PRODUCTS OF SEISMIC SHAKING?**

A report by Stephen Kumarapeli, Concordia University, Montreal, under contract to the Atomic Energy Control Board.

ABSTRACT

The New Brunswick-Maine border area, centred around Passamaquoddy Bay, is characterized by a distinctly higher level of seismic activity compared with the very low level background activity of the region. In this same general area, post-glacial deformation including faulting, has been observed in glaciofluvial and ice contact deposits and the possibility that these structures may in some way related to neotectonic movements in the area has been suggested. A study was undertaken to document these structures and to investigate their origin.

The studies show that structures related to collapse of sediments due to melting of buried ice masses are the most prominent post-depositional structures in the glacial sediments. A second group of structures includes failure phenomena such as slumping. These require the action of a mechanism leading to reduction of sediment strength which could be achieved by seismic shaking. However, such failure phenomena could also be brought about by non-seismic processes, thus a unique interpretation of the origin of these structures is difficult, if not impossible.

Since seismic shaking is the most effective, regionally extensive trigger of a broad group of failure phenomena in soft sediments, the related structures are usually spread over a large area, but are restricted to a very short time gap. Although the establishment of such space and time relationships may be feasible, for example in extensive lake deposits, it is difficult to do so in patchy, laterally variable deposits such as the glacial deposits in Passamaquoddy Bay area.

RÉSUMÉ

Le degré d'activité sismique est particulièrement élevé près de la frontière entre le Nouveau-Brunswick et le Maine à la hauteur de la baie de Passamaquoddy, comparativement au bruit de fond régional. On y observe aussi, dans les dépôts fluvio-glaciaires et les dépôts accumulés au contact de la glace, des indices de déformation, y compris des mouvements de faille. On a même suggéré que ces structures pouvaient découler de mouvements néotectoniques. Cette situation a donc fait l'objet d'une étude visant à documenter ces structures et en déterminer l'origine.

Les études générales sur le sujet ont montré que les structures les plus fréquemment observées dans les sédiments glaciaires sont dues à l'effondrement de couches sédimentaires instables par suite de la fonte des glaces sous-jacentes. Un deuxième type de structure comprend les glissements par instabilité gravitaire, qui nécessitent l'intervention d'un mécanisme, susceptible de réduire la résistance mécanique des sédiments déstabilisés. Comme d'autres processus non sismiques peuvent aussi être invoqués comme causes, il est difficile, sinon impossible, de s'en tenir à une interprétation unique.

Comme une vibration d'origine sismique est reconnue comme l'agent le plus efficace pour déclencher l'effondrement de sédiments peu consolidés, le glissement peut recouvrir une grande étendue dans un délai très court. Bien qu'il soit possible de vérifier les rapports entre la durée et la superficie, quand il s'agit de dépôts d'origine lacustre et de grandes étendues, il est beaucoup plus difficile de le faire dans le cas des dépôts dispersés et montrant de grandes variations latérales, comme ceux de la région de la baie de Passamaquoddy.

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2. INTRODUCTION

2.1 General

This report is based on field studies carried out during the period between July 2 and August 27, 1988, under contract to the Atomic Energy Control Board (Contract No: 87055-8-4069/01-SS). Additional funding for the project came from the Geological Surveys Branch, Department of Natural Resources, New Brunswick.

The study area is situated in the coastal strip around Passamaquoddy Bay, Bay of Fundy, New Brunswick (Fig. 1). Available seismic records indicate



Fig. 1. Location study area

a higher level of seismicity in this area (Barosh, 1981; Leblanc and Burke, 1985), set against a relatively low background activity (Basham et al., 1979). Interestingly, post-glacial faulting has been observed in the same general area both in bed rock (Fig. 2) and in glacial sediments (Martin, 1988; Ruitenberg, 1989). Thus, the possibility that the seismic activity and the post-glacial deformation in sediments are related is the basis for the field studies. The deformed sediments are predominantly glaciofluvial in origin and are related to the retreating Late Wisconsinian ice margin which moved northwestwards over the area around 13 ka B.P. (Rampton et al., 1984).

2.2 Background

At the present time the assessment of seismic risk in eastern Canada relies solely upon the evaluation of historical and current seismic data. The underlying assumption of this approach is that damaging earthquakes will occur in areas, or zones, that have a record of such seismic activity. However, seismic data have only been collected for a maximum period of about 450 years, and that too, only for the area referred to as the Charlevoix Seismic Zone (Basham et al., 1979) northeast of Quebec City. Elsewhere, the historical records do not go back more than about 200 years. From the foregoing it is apparent that the period of time covered by the historic seismic record is too short to be representative of a time period appropriate for geological processes.

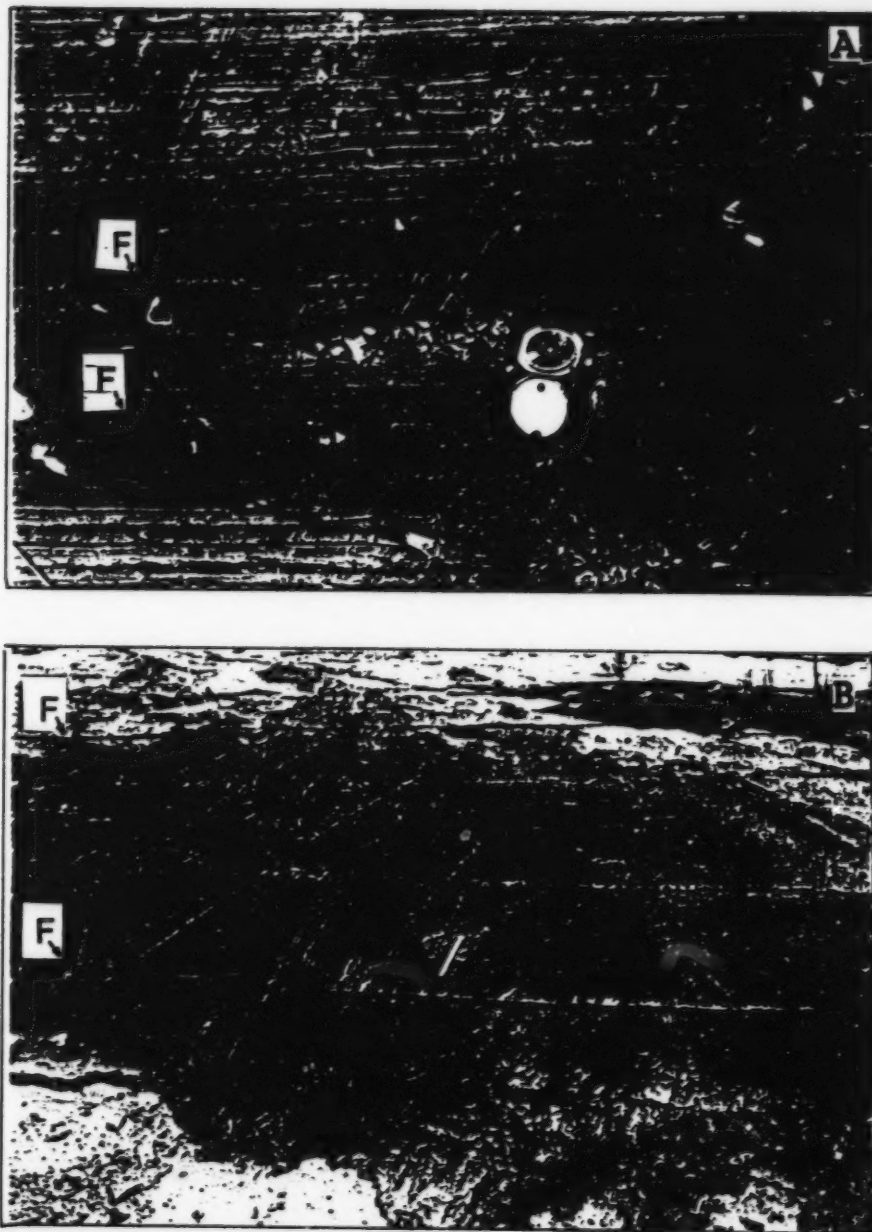


Fig. 2. Post-glacial microfaults in bedrock, southern New Brunswick. A: reverse microfaults (F) in steeply dipping slate, hill side on City Road near the City Hospital, Saint John; faults strike at 55° and dip 70° southeast to near vertical and clearly displace glacial striae. B: vertical microfaults (F) striking 60° - 88° displacing glacial striae (maximum vertical displacement 0.5cm) on dioritic outcrop, about 4.5 km north of Lepreau.

Despite the rigorous statistical treatment of seismic data, the employment of earthquake records alone can lead to surprises regarding the future occurrences of major earthquakes. Examples in eastern Canada include the 1935 Timiskaming (Quebec) earthquake ($M=6.0$), the 1944 Cornwall (Ontario) earthquake ($M=5.9$) and the Nov. 25, 1988 earthquake ($M=6.0$) south of Chicoutimi, Quebec, all of which were centered in areas that had previously been devoid of any felt reports or instrumental recordings of major seismic activity. An additional illustration comes from China. There, seismic records go back at least 2,000 years, yet nothing in those records prepared the people for the 1976 Tangshan earthquake ($M=7.8$) which killed several hundred thousand people.

The examples cited above serve to illustrate that seismic risk, in areas unknown to have been previously affected (or were only slightly affected) by large earthquakes, may be underestimated. However, this may be overcome if the knowledge of seismic history were to be extended much further back in time than seismic records alone allow. To accomplish this, a well co-ordinated program embodying carefully conceived geological, geophysical, seismological, remote sensing and rock stress investigations are required to supplement the existing seismic information. This study addresses the question of origin of deformation in unconsolidated glacial sediments in a seismically active area.

2.3 Objectives

The objectives of this study are: (1) to collect data on deformation in glacial and post-glacial sediments in the study area, in order that they may be incorporated into a data base to be set up by the Multi-Agency Group for Neotectonics in Eastern Canada (MAGNEC); (2) to evaluate the origin of the structures in the context of seismic activity in the area.

3. SEISMICITY AND SEISMOTECTONICS OF PASSAMAQUODDY BAY AREA

The Passamaquoddy Bay area is one of two areas in New Brunswick with an apparent concentration of earthquake activity, the other being the Miramichi Highlands. Leblanc and Burke (1985) have re-evaluated four historical earthquake records in the Maine-New Brunswick border region (which includes the Passamaquoddy Bay area) and have shown that the 1817 (m_b : 4.5 to 5) and 1904 (m_b : 5.9) events and most probably the 1869 (m_b : 5.7) earthquake occurred in the Passamaquoddy Bay area. They concluded that earthquakes of magnitude 5.5 to 6 have occurred in the New Brunswick-Maine border region during the previous 170 years. In 1983-84, a series of six M3 earthquakes occurred near Passamaquoddy Bay (Adams and Basham, 1989). Such low level seismicity is indicative of the presence of seismogenic structures in the area. Focal mechanisms from the general region indicate dominantly thrust faulting in response to northeast to east-directed compression, but the one mechanism available for the Passamaquoddy area does not fit this general pattern (Adams and Basham, 1989).

Correlation of seismic activity with specific geological features is hampered by uncertainties in epicentral locations (Rast et al., 1979). However, several workers (e.g. Burke, 1984) have drawn attention to the fact that if epicentres are plotted on a small scale geological map of the Passamaquoddy Bay area, a correlation is suggested with the Oak Bay fault zone. This fault zone trends NNW whereas most of the mapped faults in the area are parallel or subparallel to the northeasterly Appalachian trends (Fig. 3; Leger and Williams, 1986; McLeod and Rast, 1988). Movements on the Oak

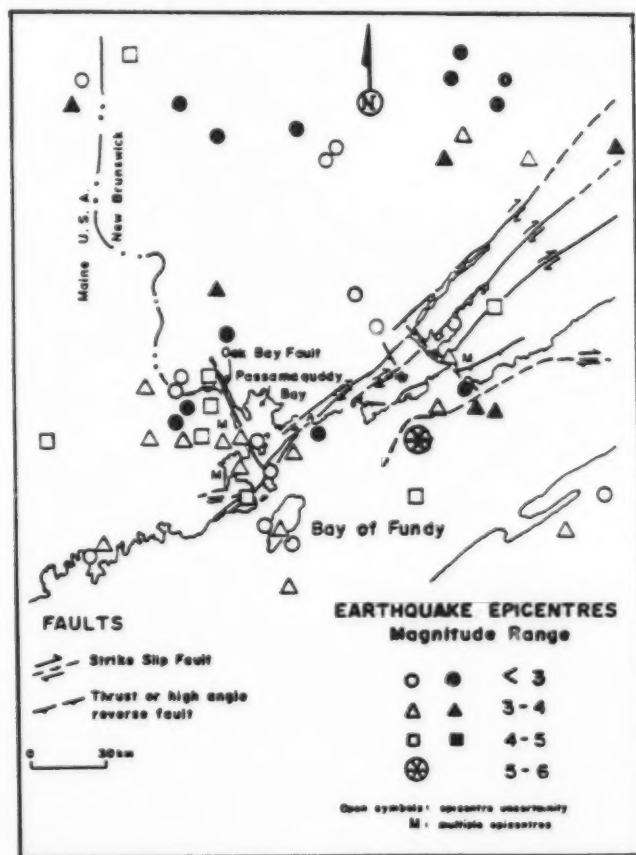


Fig. 3. Major fault patterns and the distribution of epicentres in Southern New Brunswick. Fault patterns from Leger and Williams (1986) and McLeod and Rast (1988), seismic data from Burke (1984)

Bay fault zone are sinistral and strike-slip, but evidence for recent movements on it is inconclusive (Burke, 1984; Burke and Stringer, 1988). The fact that major fault zones (the NNW trending Oak Bay zone and the NE trending faults) intersect in the Passamaquoddy Bay area may be a factor conducive to localization of stresses.

4. FIELD STUDIES

4.1 General

Several examples of deformation (faulting and folding) in glacial sediments of the study area were shown to me during a one-day field trip led by Dr. A.A. Ruitenberg of the New Brunswick Department of Natural Resources. Other localities for investigation were selected on the basis of section descriptions (for example active pits with cuts > 3m were preferred) of gravel pits and other natural exposures in Topical and Open File reports of the New Brunswick Department of Natural Resources on granular aggregate resources. The existence of these reports, which sometimes contain passing reference to structural information, was brought to my attention by Mr. A. Seaman, of the New Brunswick Department of Natural Resources, who also made the reports available to me. A total of 41 sand-gravel pits or pit complexes were examined. These are listed in Table I. Of these, 8 sand-gravel pits contained sections with interesting structures. These are designated as work sites (Fig. 4) and their structures are described and discussed below.

Table 1

List of sand-gravel pits: Passamquoddy Bay area, N.B.:
examined for post-glacial deformation

NTS Map No.	N.B. Dept. Natural Resources No.	Site No. (this report)	Source
21G/1	LM75-36	1	Loshe 1975
	LM75-39	-	
	LM75-5	-	
	LM75-15	-	
	LM75-28	-	
	LM75-10	-	
21G/2	G2 56	-	Finamore and Seaman 1968
	G2 54	-	
	G2 169	-	
	G2 53	-	
	G2 171	-	
	G2 156	-	
	G2 43	-	
	G2 37	-	
	G2 145	2	
	G2 144	-	
	G2 143	-	
	G2 142	3	
	G2 14	4	
	G2 21	-	
	G2 22	-	
	G2 119	5	
	G2 23	-	
	G2 16	-	
	G2 107	-	
	G2 108	-	
	G2 1	6	
21G/3	G3-24	7	Thibault 1982
	G3-21	-	
	G3-20	-	
	G3-19	-	
	G3-17	-	
	G3-16	-	
	G3-15	-	
	G3-13,14	8	
	G3-4	-	
	G3-7	-	
	G3-6	-	
21G/5+6	G6-25	-	
	G6-13	-	
	G6-16	-	

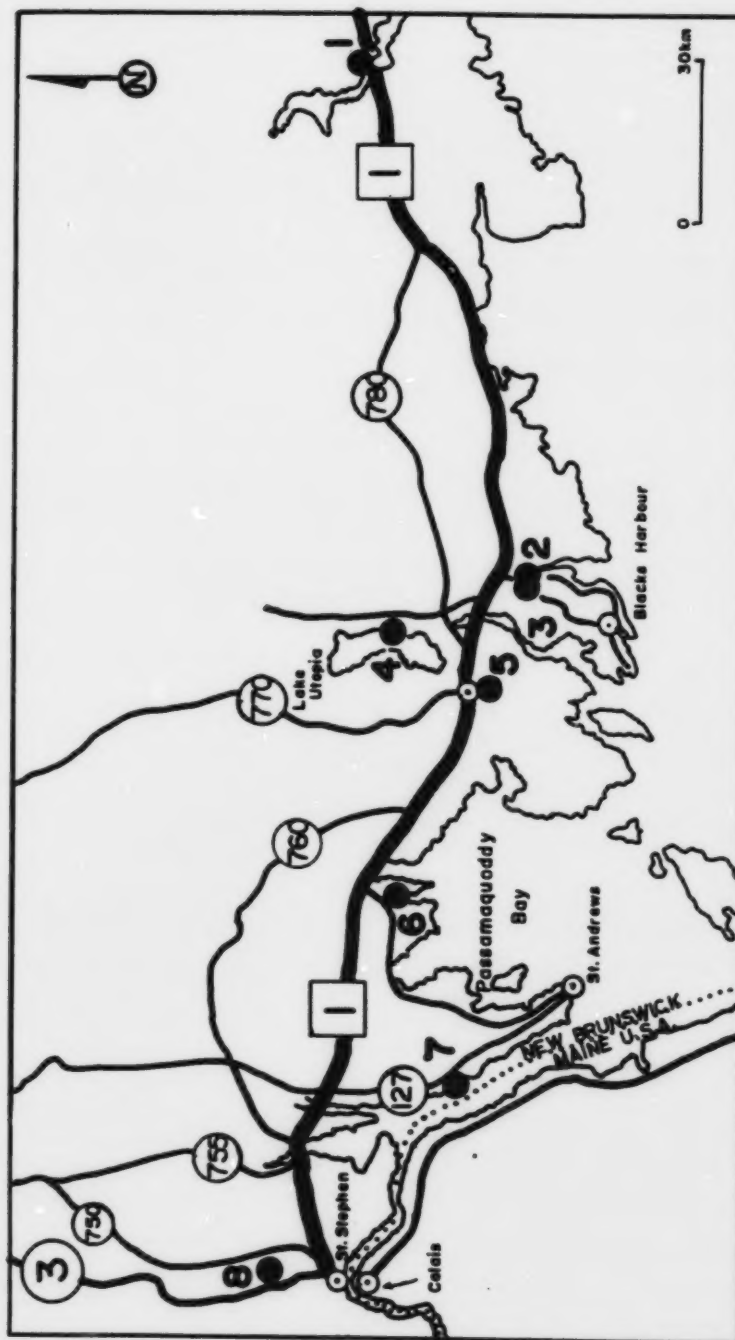


Fig. 4. Location of the eight work sites (filled circles).

4.2 Site I Musquash River (NTS 21G/1, for location see Figs. 4 and 5)

This gravel pit is located about 100 m east of the Musquash River and 300 m north of Highway 1 (St. Stephen to St. John, N.B.) and can be reached from the Highway via a northbound secondary road (Fig. 5). A de_posit of probable ice contact origin is exposed on the southeast wall of a crescent-shaped cut which has not been worked recently. Only the upper 3 m of the approximately 12 m section is exposed.

This section consists of a sequence of interbedded fine to coarse sand and gravel. Dips are gentle ($<20^{\circ}$) to the northeast and appear to be related to crossbedding. An approximately 8m long segment of the section shows post-depositional deformation. The most prominent structural element is a set of sub-parallel (strike 150° to 160°), high-angle (dips 55° to 85° SW) reverse faults (Figs 6,7,8) with a maximum vertical displacement of 35 cm on a single fault (Fig. 8). Other characteristics associated with the faults are a general decrease in displacement up section, pronounced drag of faulted beds and the common presence of oriented pebbles and silt injections (these are actually infiltrations from above). The faulted section also shows some folding (Figs. 7,9) and some of the sandy beds in the section are substantially thickened (Fig. 7).

McDonald and Shilts (1975) attributed high-angle reverse faults in glaciofluvial sediments to the collapse of the sediment

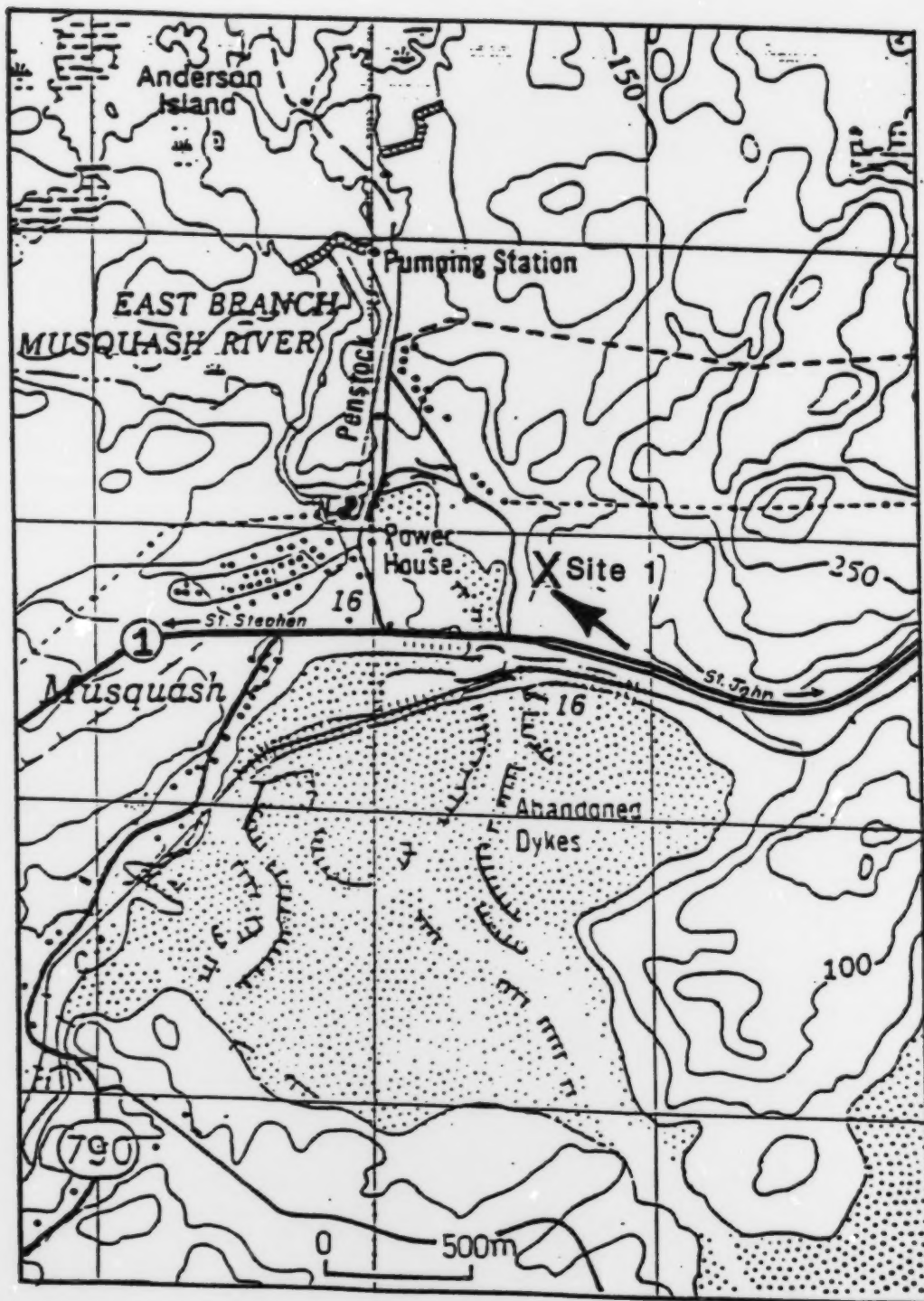


Fig. 5. Location: site 1, Musquash River. Base map from 21G/1, Department of Energy, Mines and Resources, Canada

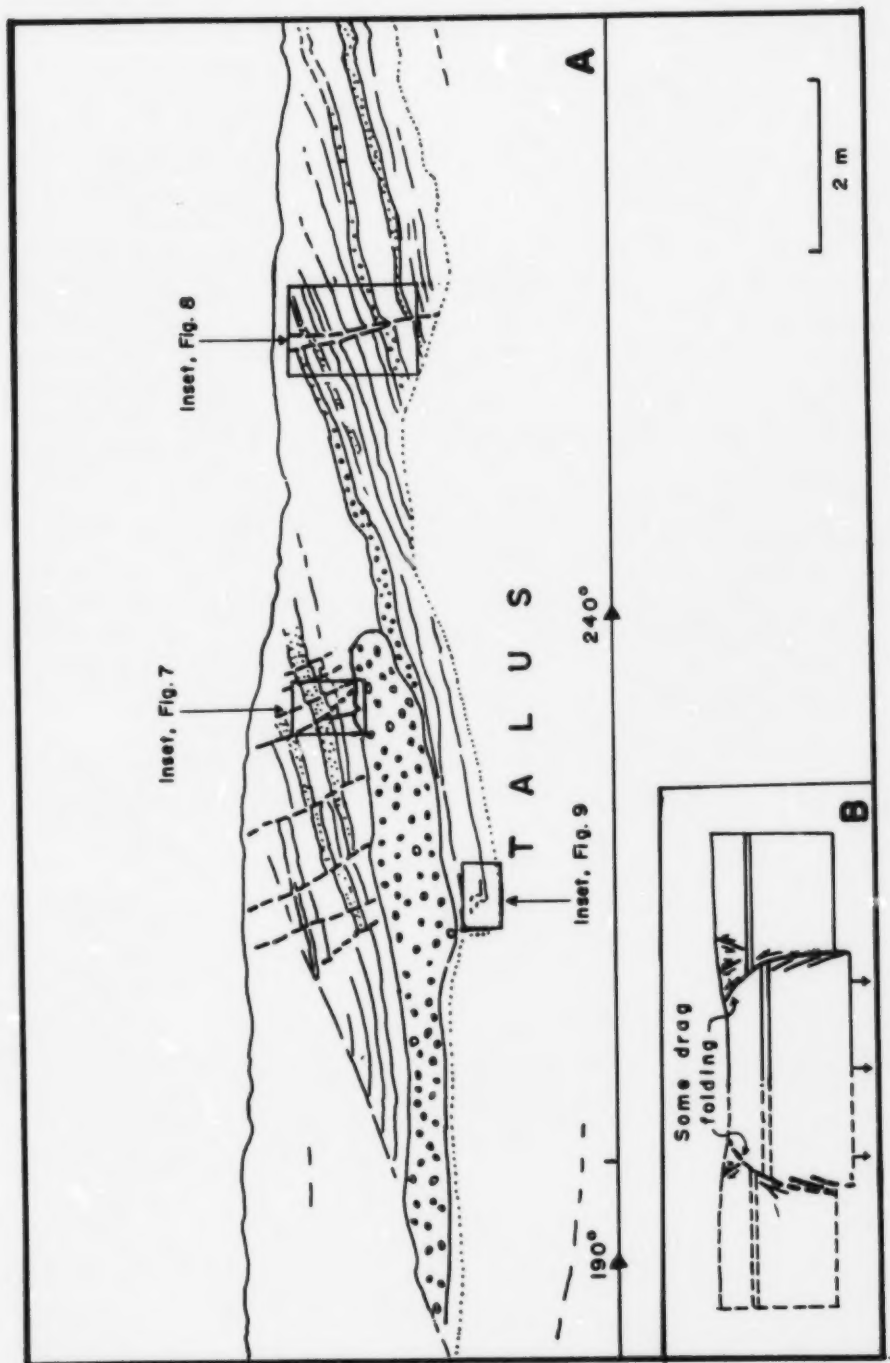


Fig. 6. Faulted section of sand and gravel at site 1. For location see Figs. 4 and 5. Faults: heavy broken lines. B: Fault pattern from type II experiments of Sandford (1959)

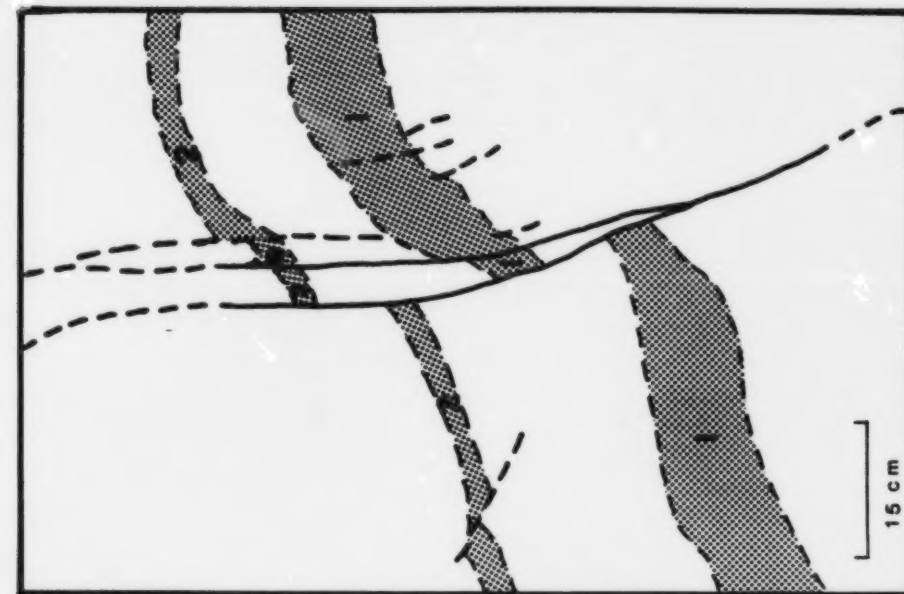


Fig. 8 Splaying high-angle reverse fault at site 1. For location of frame see Fig. 6A.

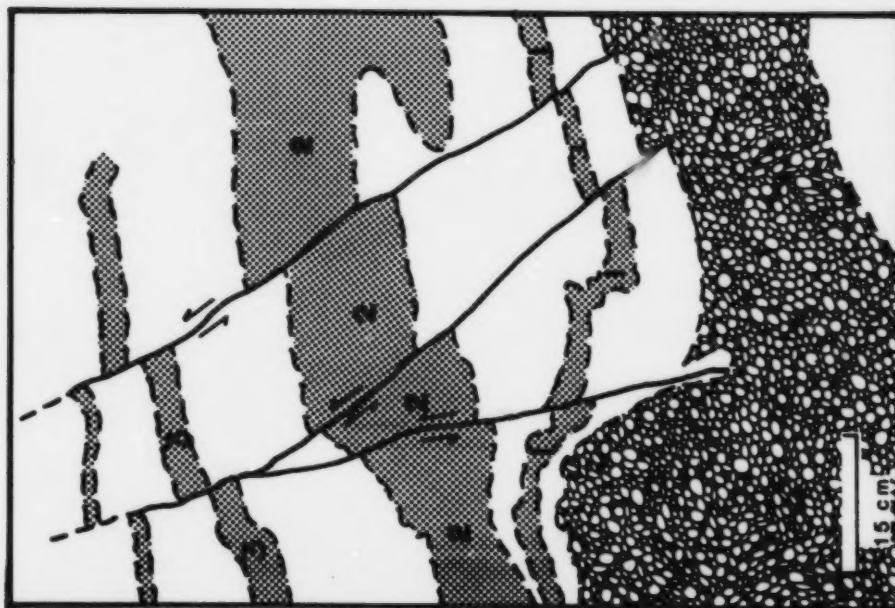


Fig. 7. High-angle reverse faulting accompanied by folding and thickening of beds at site 1. For location of, the frame see Fig. 6A.

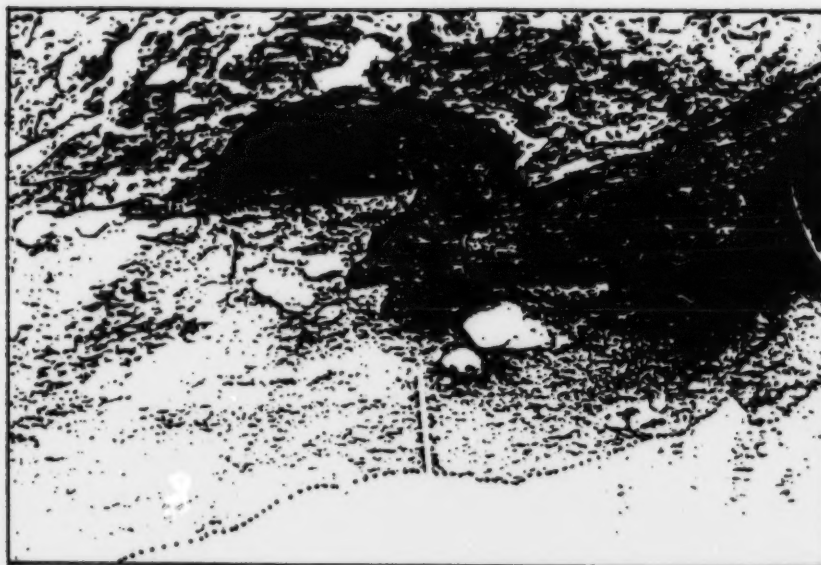


Fig. 9. Folded and thickened bed at site 1. For location of frame see Fig. 6A. Pencil for scale.

body as masses of buried ice melted. They argued that fault patterns produced by this mechanism are similar to those predicted from Sanford's (1959) scale model experiments with fine sand. Figure 6B show the fault pattern produced by type II experiments of Sanford in which a step discontinuity was applied by vertical displacement of the lower boundary. This is analogous to collapse of the overlying sediment into the void created by melting of buried ice. The fault pattern in the Musquash River section is broadly similar to the pattern formed over one edge (right edge in Fig. 6B) of Sanford's model II experiment (the pattern consists of a series of reverse faults rather than a single fault). The upward convexity of faults in the model experiment is not shown by faults in the section which may be due to truncation of the upper part of the section by erosion. According to this scheme, one edge

of the buried ice mass was beneath the faulted section and the main mass lay to the left (Fig. 6).

4.3 Site 2 Pennfield (NTS 21G/2, for location see Figs. 4 and 10)

This site is located about 1 km south of Pennfield corner in the Pennfield outwash deposit (Finamore and Seaman, 1988) and can be reached from Highway 1 (St. John - St. Stephen, N.B.) via Highway 778. The sand and gravel quarry at the site is worked on a small scale; a visit to the site in August 1989 showed no trace of the section studied in August 1988.

The cut at this site is about 8 m deep, of which the lower 4 m are talus covered. It exposes a lower, southwest dipping, cross-bedded sequence (approximately 4 m thick) consisting mainly of gravel and an upper, nearly horizontal sand and gravel sequence. A thinly bedded silty sand unit in the lower sequence shows slump strain including some bedding disaggregation. The silty sand unit has a blade-like cross section (Fig. 11) which is about 12 m long with a maximum thickness of about 1.5 m. It is sandwiched between two gravel beds, but its top is clearly an erosion surface (2 in Fig. 11). The slumped sheet is about 0.5 m thick and passes downwards to undisturbed stratigraphy. At the top, it is truncated by an erosion surface (1 in Fig. 11) in the silty sand unit.

The dominant structural elements in the slumped sheet are recumbent, isoclinal, early folds with nearly horizontal axial

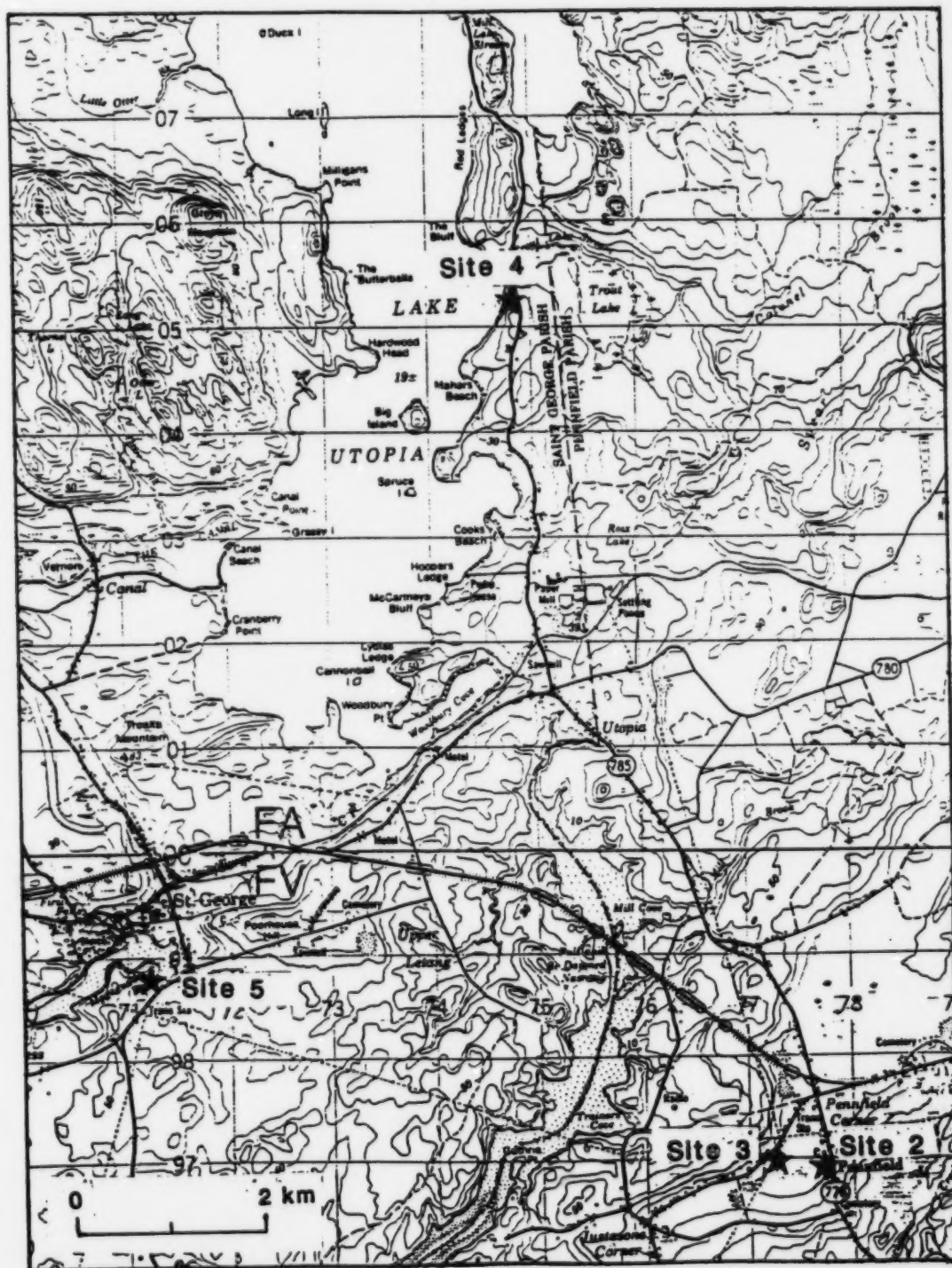


Fig. 10. Locations: sites 2 to 5. Base map from 21G/2, Department of Energy, Mines and Resources, Canada.

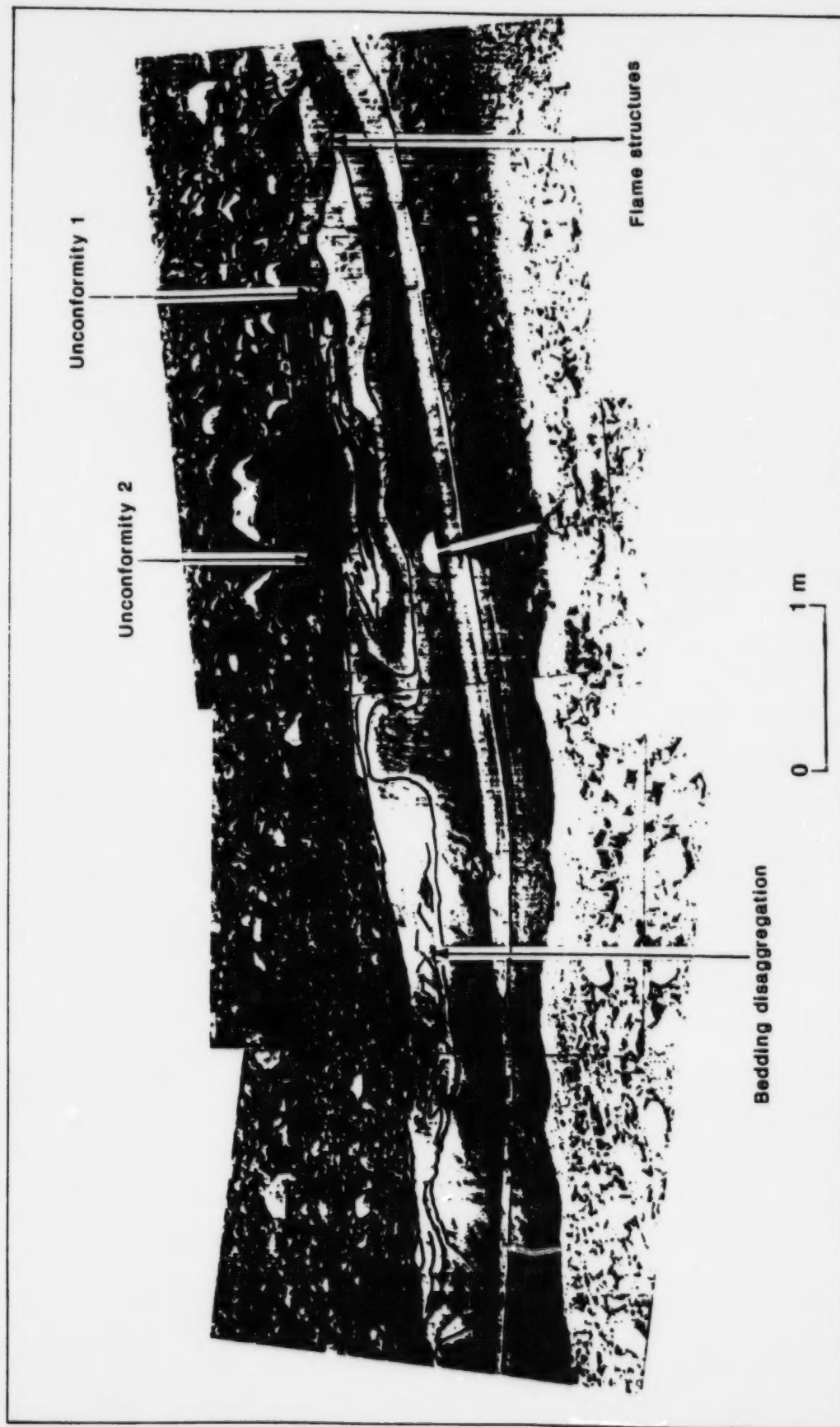


Fig. 11. Section at site 2 showing slump strain and bedding disaggregation in a thinly bedded silty sand unit. For location of section see Figs. 4 and 10.

surfaces, which have been folded by open late folds (including a box fold) with sub-vertical axial surfaces. The hinge lines of both sets of folds are nearly parallel (strike 260°) and probably conform with the normal to the paleoslope. Also present in the slumped layer are flame structures (Fig. 11). The folds as well as the flame structures verge towards the inferred paleoslope. One segment of the slumped sheet shows some bedding disaggregation (Fig. 11).

The absence of microfaults in the deformed section and the lack of a clear décollement surface suggest that the deformed sediment was in a liquidized state. The surface on which the sediment flow took place appears to have been thrown into ripples and the later folds may have formed by draping of the slumped sheet over such ripples. An earthquake shock is a possible triggering mechanism for this type of deformation.

4.4 Site 3. Pennfield (NTS 21G/2, for location see Figs. 4 and 10)

This site is about 600 m west of site 2 and is also located in the Pennfield outwash deposit. It can be reached from Highway 1 (St. Stephen - St. John, N.B.) via Highway 776. The active sand and gravel pit at the site exposes horizontally stratified, poorly sorted sand and gravel. The cut is about 10 m deep but only the upper 3 m are exposed. A high-angle reverse fault (strike 165°) with a vertical displacement of about 20 cm was observed on the

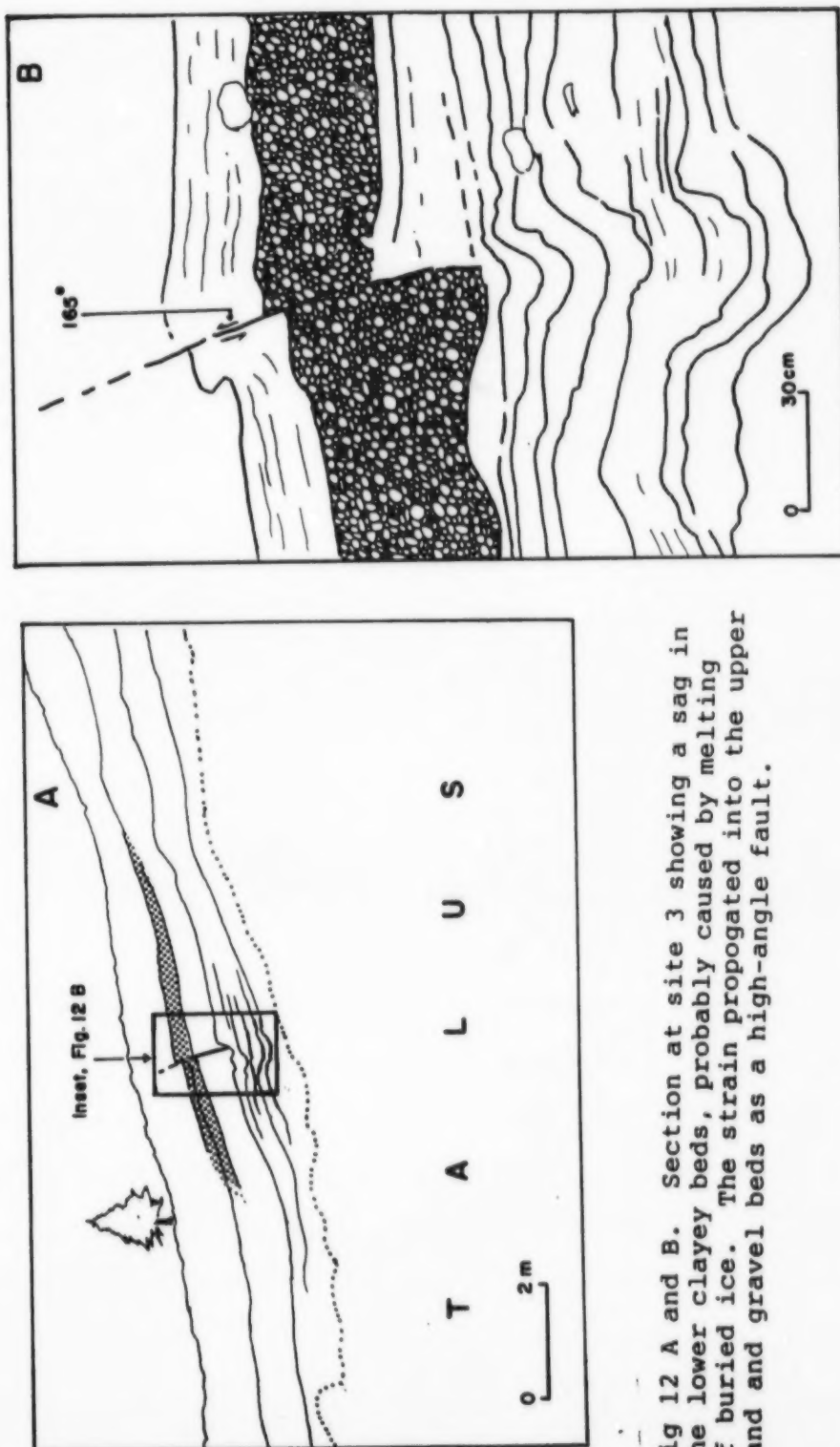


Fig 12 A and B. Section at site 3 showing a sag in the lower clayey beds, probably caused by melting of buried ice. The strain propagated into the upper sand and gravel beds as a high-angle fault.

south wall of the cut. Clearing the talus to expose the downward extension of the fault revealed that it is related to an isolated synclinal fold in the sediment (Fig. 12). Melting of a small mass of buried ice probably caused sagging of the sediments and the strain appears to have propagated up section as a fault. Thus, it is unlikely that this fault is related to neotectonics or seismicity.

4.5 Site 4. Lake Utopia (NTS 21G/2, for location see Figs. 4 and 10)

This site is on the east side of Lake Utopia and can be reached from Highway 1 (St. Stephen - St. John, N.B.) via Highway 785. The inactive pit at this site has a maximum depth of about 15 m but the lower 60% is talus covered (Fig. 13). The exposed section consists mainly of a stratified sequence of well sorted fine sand with some silty horizons. This sequence is down-faulted to the west (toward the lake) and is unconformably overlain by the westward thickening wedge of poorly sorted sand and sand supported pebbles and cobbles. Beneath the wedge of coarse clastics, the sandy beds dip at 30° to 35° to the west (towards the lake). East of the clastic wedge, the dips are to the east ($\approx 20^{\circ}$) but decreases to near zero at the east end of the cut. The strike of the sequence is approximately 170° and is nearly parallel to the trend of the lake (Fig. 10).

The most prominent structural element of the section is a set of sub-parallel normal faults which range in strike from 155° to 170° , and dip to the west at 40° - 60° (Figs. 13 to 17)).

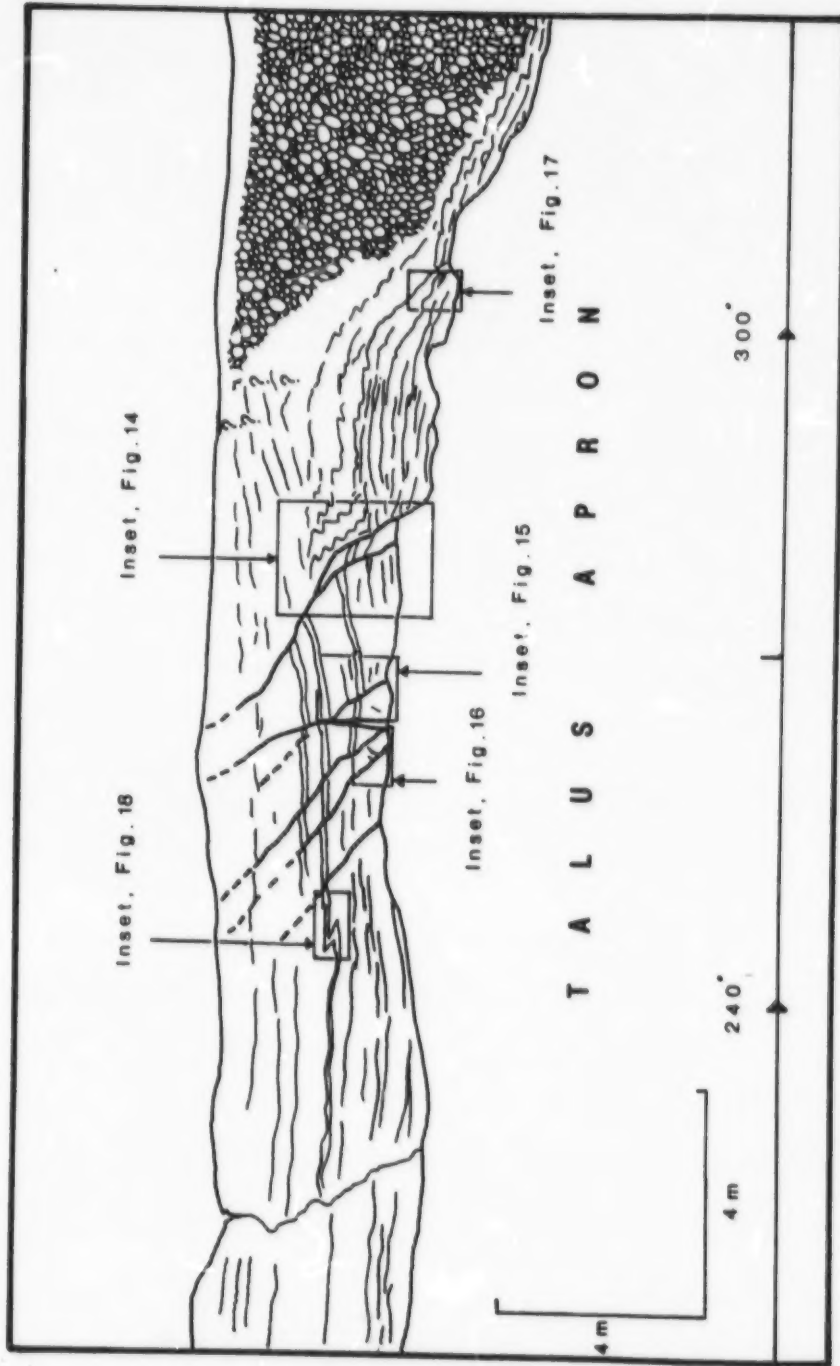


Fig. 13. West dipping normal faults developed in predominantly sandy beds site 4. For location see Figs. 4 and 10. The faults are probably slip surfaces related to a slide.

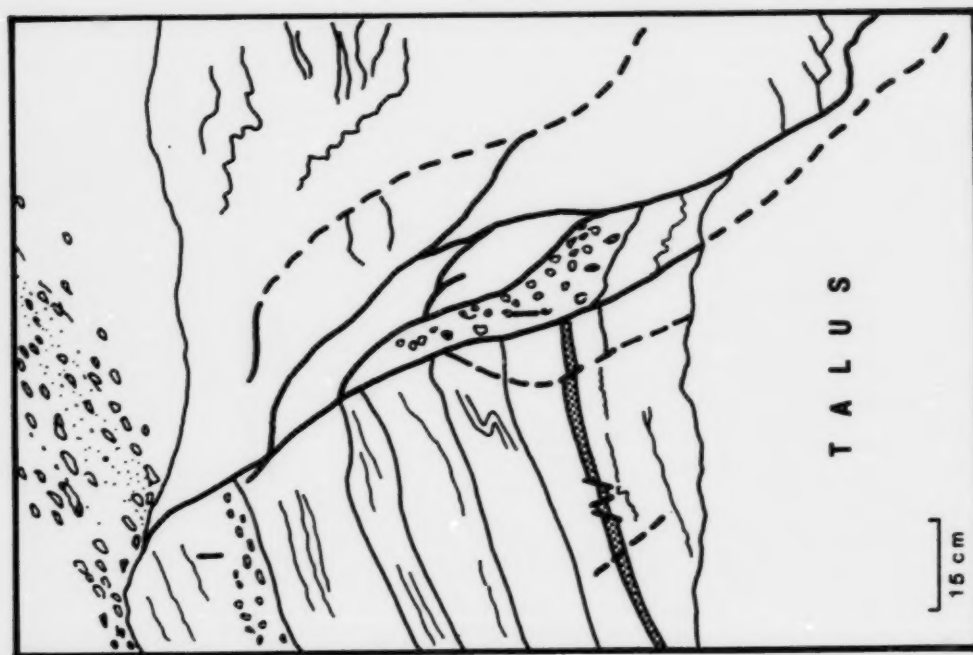


Fig. 14. Braided normal fault at site 4. This is the largest (maximum downthrow 3m) fault at the site. Location of frame shown in Fig. 13.

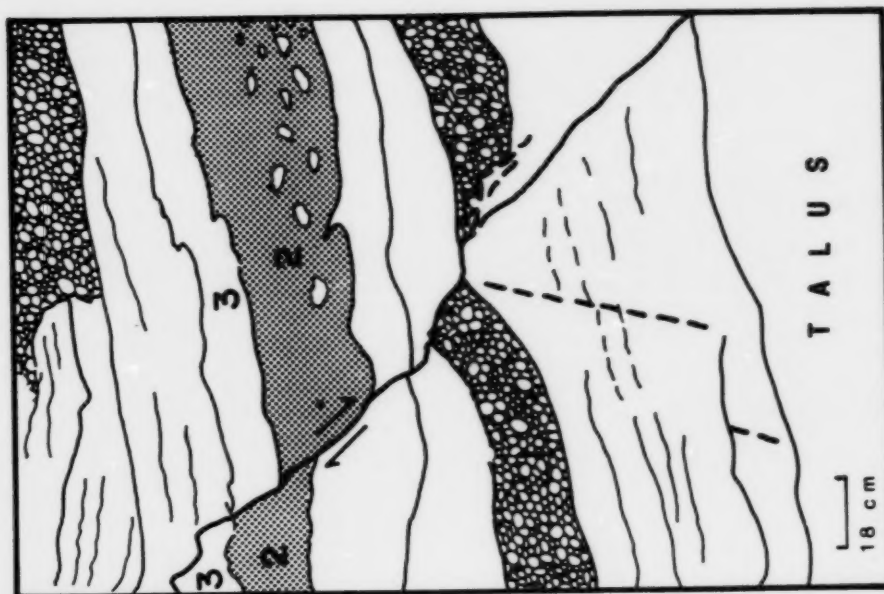


Fig. 15. Example of a normal fault with irregular fault surface from site 4. For location of frame see Fig. 13.

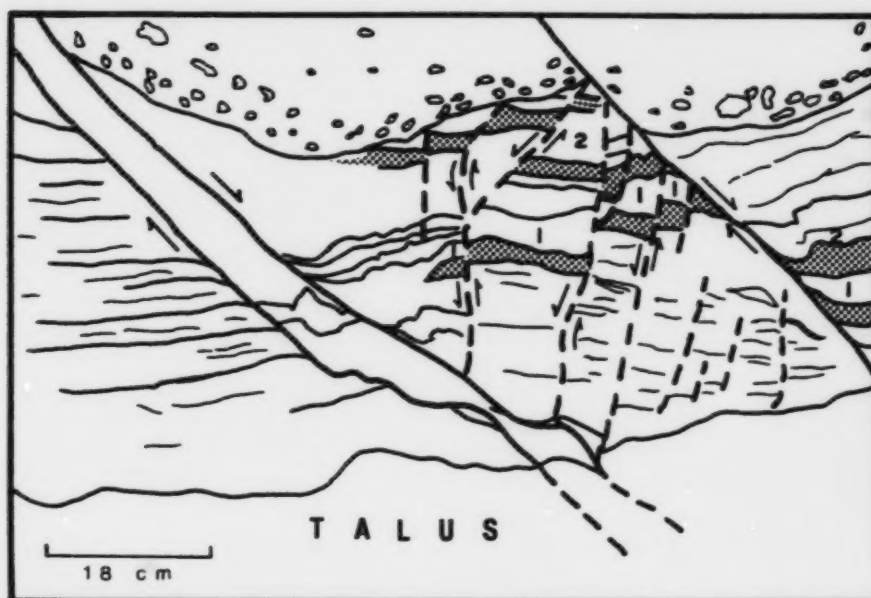


Fig. 16. Fault block with minor antithetic faults from site 4. For location of frame see Fig. 13.

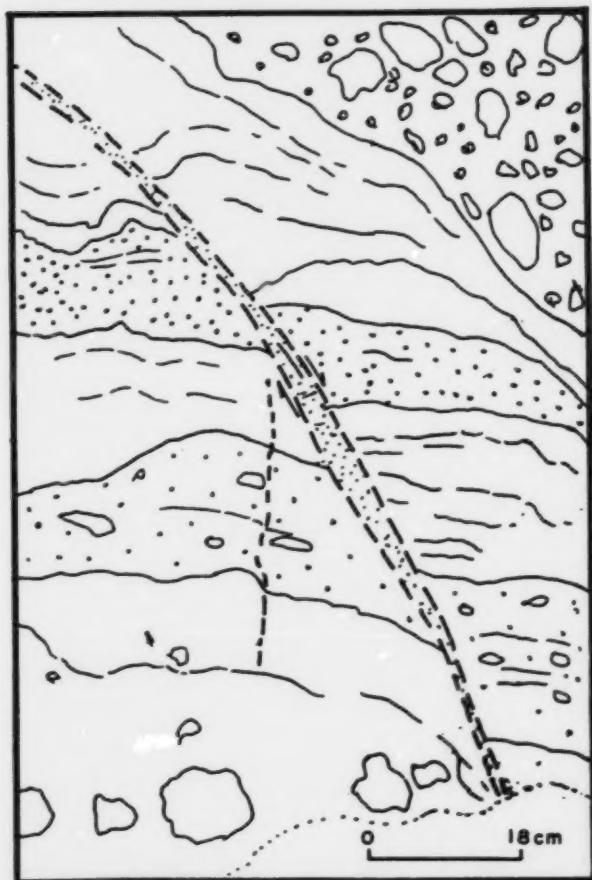


Fig. 17. Example of normal fault with silt infilling from site 4. For location of frame see Fig. 13.

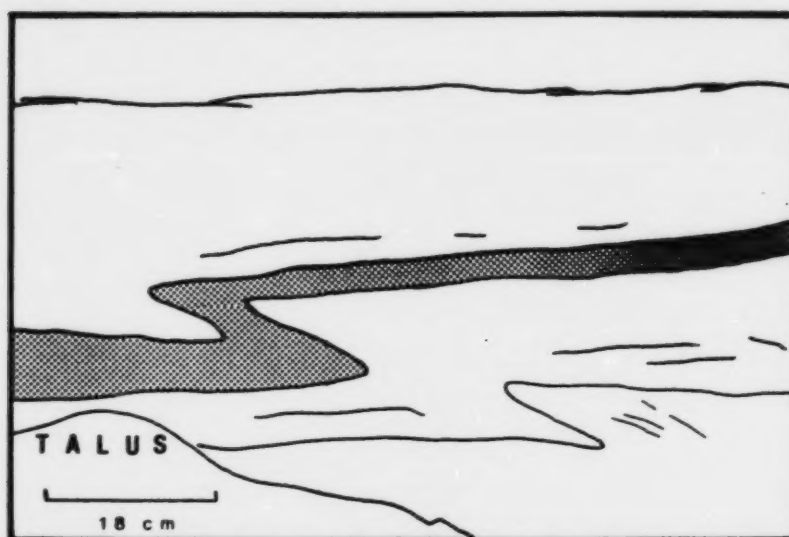


Fig. 18. S - fold in sandy beds, probably formed by downdip slippage of beds by gravity.

The faults divide an approximately 6m wide section of the sandy sequence into a number of fault blocks which are also broken by minor antithetic faults (Fig. 16) some of which are clearly younger than the principal normal faults. Cumulative downthrow in the section exceeds 4m.

Some of the east dipping sandy beds show east verging S-folds (Figs. 14, 18) with fold axes nearly parallel to the strike of bedding. Axial planes of these folds are sub horizontal to west dipping ($\sim 20^\circ$); in some instances their overturned limbs are sheared by west dipping ($\sim 20^\circ$) reverse faults (stretch faults). It is difficult to attribute the normal faults and folds in the section to a single stress regime. The folds probably formed by slow downdip slippage of beds whereas the principal set of normal faults appears to comprise slip surfaces related to a slide. The

slip surface on which the main mass movement took place is represented by the braided fault shown in Figure 14. The other normal faults probably represent crown cracks with small amounts of rotational sliding. The sediments at this site are probably ice contact deposits (Finamore and Seaman, 1988). Removal of lateral support by ice melting may have created the gravitational instability for the slide. The coarse clastic wedge probably represents a flow-till deposit. The emplacement of this deposit and the sliding may be related to a single gravity induced event.

4.6 Site 5. St. George (NTS 21G/2; for location see Figs. 4 and 10)

The site is located about 1 km south of St. George on the south side of Magaguadavic river and can be reached from Highway 772 leading to Black Bay (Fig. 10). The site is in the St. George moraine (Finamore and Seaman, 1988) and has several sand and gravel quarries of which only one had been worked recently.

4.6.1: The cut shown in Figures 19A and B is over 20 m deep but about half of it is covered by talus. The lower part of the exposed section consists of a cyclical succession of thinly laminated beds of silty sand and poorly sorted coarse sand with varying amounts of rounded to sub-rounded pebbles. The top of this succession is marked by a thick (~ 2 m) pebbly sand bed (2 in Fig.

19B). It is overlain by a succession of thinly laminated clayey silt (3 in Fig. 19B). Faulting is evident only in the lower sequence but folding extends into the upper sequence as well. Small folds with amplitude up to 15 cm, high-angle faults with small (<30 cm) displacements and flame structures are the most prominent structural elements of the section. The deformed beds strike at 030° to 060° with dips of about 20° SE in the western part (right in Fig. 19B) and 15° NW in the eastern part defining a gentle synclinal flexure which probably originated as a syndepositional feature related to depositional slopes but may have been accentuated by later faulting. Folding is most prominent in a bed (1 in Fig. 19B) of thinly laminated silty sand. Small folds with a variety of shapes: s-folds with sharp hinge lines (Fig. 20), z-folds (Fig. 21), buckle folds (Fig. 21), refolded folds (Fig. 22) and small monoclinical flexures related to faults (Fig. 21) are present. In general, axes of folds are parallel to the strike of bedding and hence to the paleoslopes. Axial planes are flat-lying to inclined (up to 45°). On the east limb of the synclinal flexure, folds are west verging whereas on the west limb, the folds are east verging. Folds tend to be disharmonic, being most pronouncedly developed in the silty horizons. Thus, the deformation has an intraformational character and is probably due

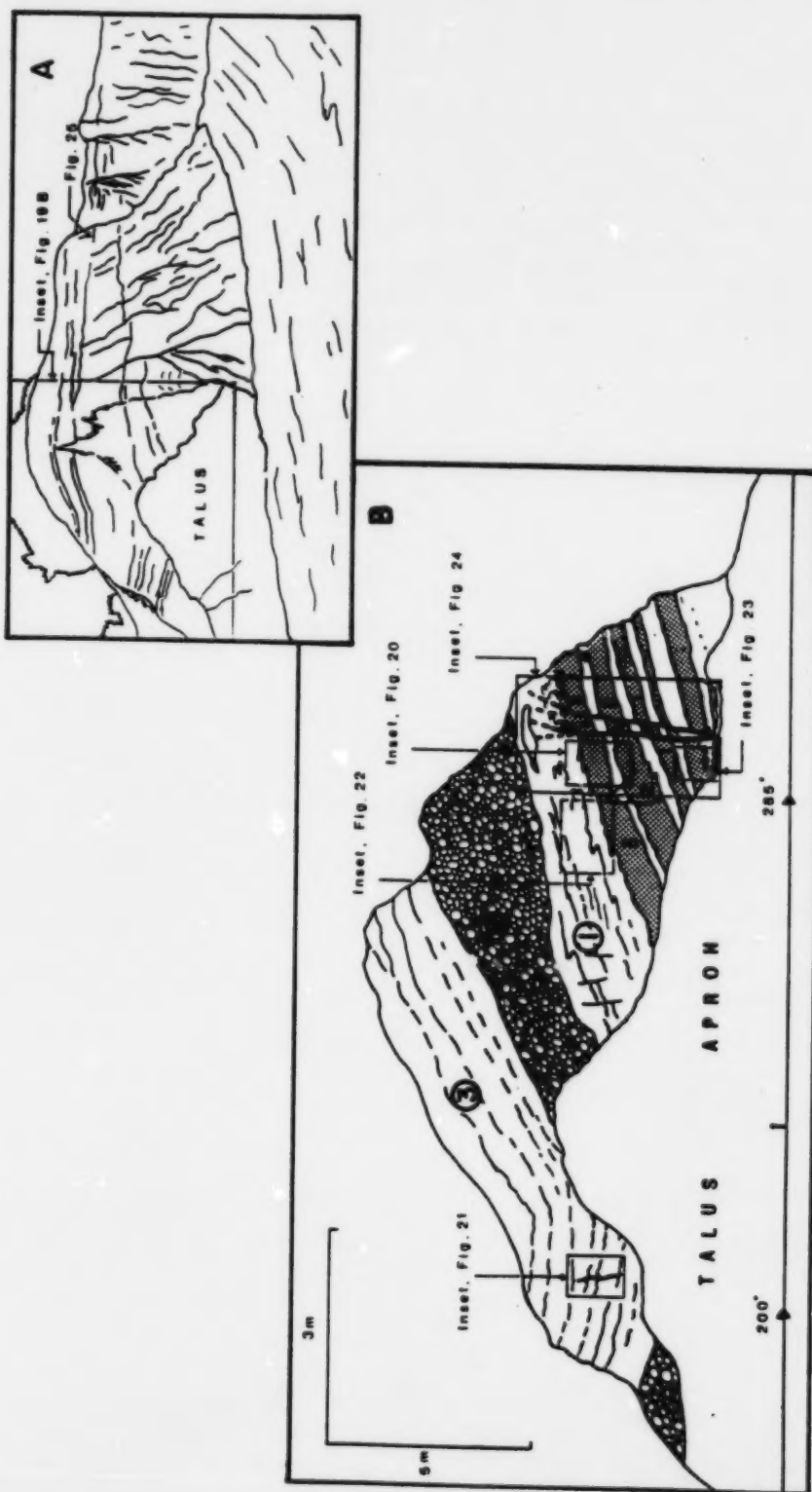


Fig. 19 A & B. Small faults and folds developed on the flanks of a gentle synclinal structure in glacial sediments of the St. George moraine at site 5. For location of site see Figs. 4 and 10. Subsidence (melting of buried ice?) of the axial part of the syncline probably caused the faulting. Folding appears to have resulted from slippage of beds towards the axis of the syncline. Details of the structure are shown in Figs 20-24.

to gravitationally induced movements. The fold pattern is consistent with slippage of beds towards the axis of the synclinal flexure.



Fig. 20. S-folds with sharp hinge lines in thinly laminated silty sand at site 5. For location of frame see fig. 19.B.



Fig. 21. S-folds and monoclinial flexures in silty sediments at site 5. For location of frame see Fig. 19B.



Fig. 22. Refolded fold in thinly laminated silty sand at site 5. For location of frame refer to Fig. 19B.

Numerous, small (<30 cm displacement), high-angle faults occur in the lower part of the section. Some of them are clearly syndepositional growth faults whereas others appear to be post-depositional. Downward terminations of most of them are not visible but a few die out within the section (Fig. 23).

The largest fault exposed is in the west flank of the cut. It is a near vertical fault (Fig. 24) which strikes at 170° . The fault bifurcates upwards and produces a splay in the folded silty sand bed and dies out within this bed. Beds show abrupt disruptions

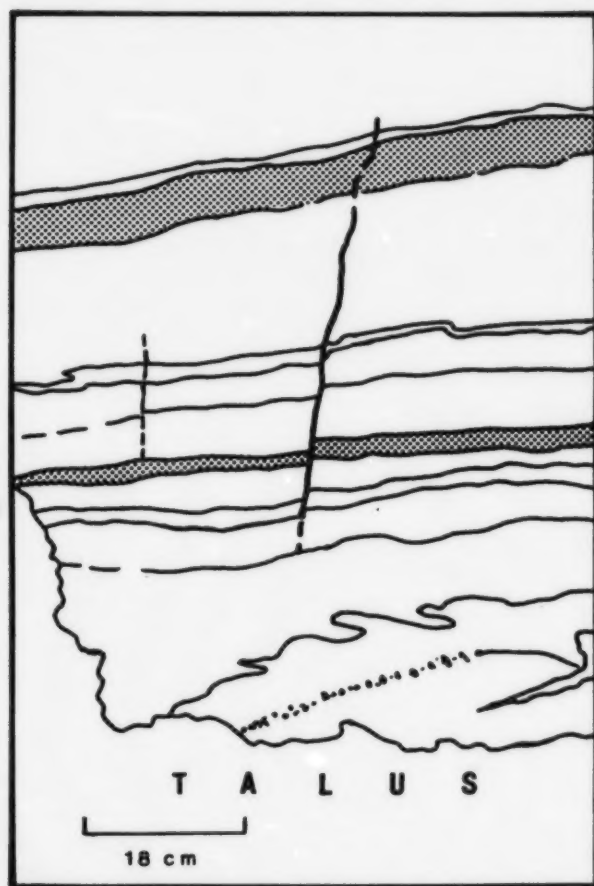


Fig. 23. Flame structures (just above the talus line) in silty sand at site 5. Note that the microfaults in the section begin and terminate within the section. For location of the frame see Fig. 19B.

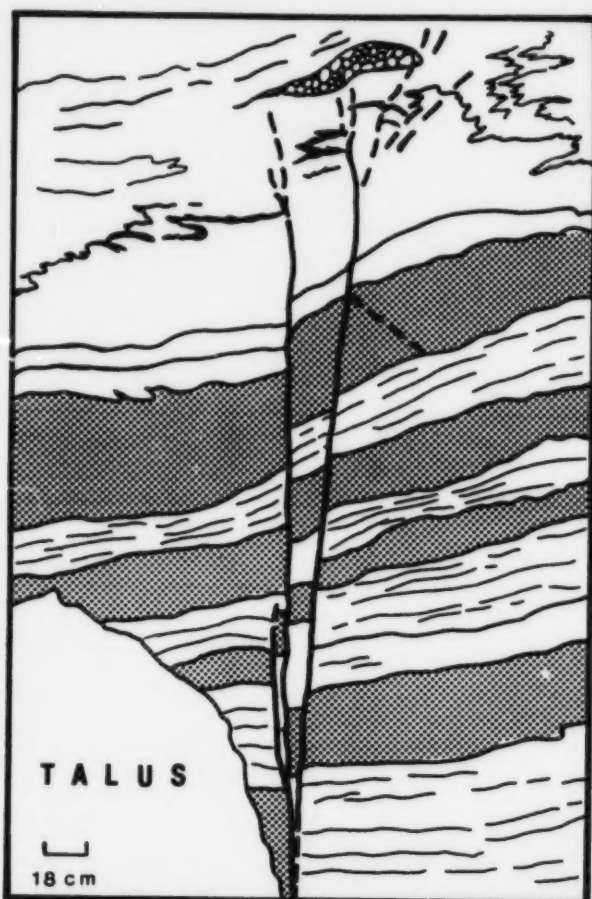


Fig. 24. Details of the largest (maximum displacement 25 cm) fault observed at site 5. For location see Fig. 19B. Note that the beds terminate abruptly against the fault.

against the fault(s) with little or no drag. The overall fault pattern in the section appears to be related to subsidence of the axial part of the synclinal flexure. The reasons for subsidence is not clear but may be due to dewatering and compaction of sediments or melting of buried ice. Enhancement of initial dips resulting from subsidence may have favoured the gravitationally induced mass movements which caused folding.

Flame structures (Fig. 23) are present in the deformed lower part of the section. Their vergence is also consistent with slip of

beds towards the axial part of the synclinal flexure. Load casting, resulting from vertical anisotropy, accompanied by bedding-parallel slippage may have produced these structures.

4.6.2: About 20 m south of the section described in 4.6.1, there is clear evidence for slumping in the lower silt-pebbly sand sequence (Fig. 25; for location see Fig. 19A). Although extreme deformation by flowage folding has occurred, original structures are still, to some extent preserved. The deformed beds are unconformably overlain by the upper clayey silt succession (Fig. 25).

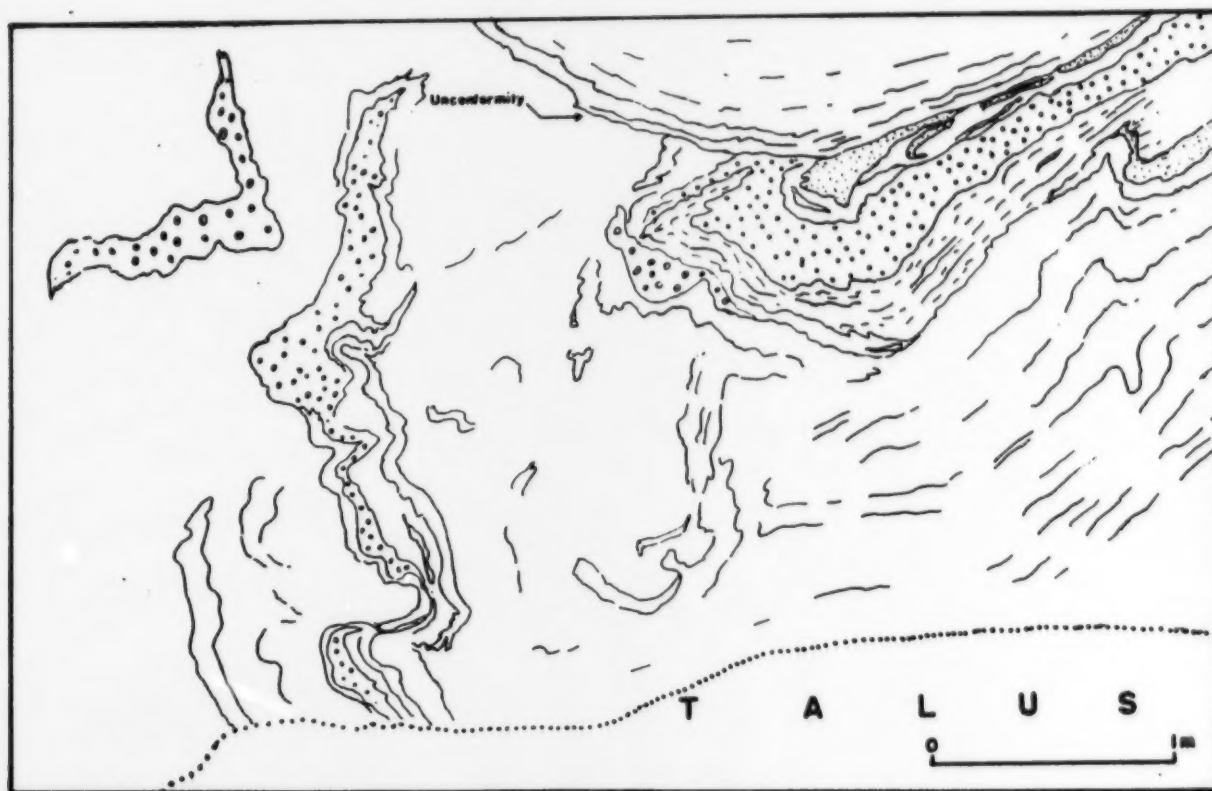


Fig. 25. Slumped section at site 5. For location see Fig. 19A.

4.6.3 In August 1989, site 5 (St. George) was revisited wherein a new pit, just south of the cut shown in Figure 19A, was in operation. The walls of this pit show gravitationally induced movements down limbs of synclinal flexures which are clearly syndepositional structures in channel-fill deposits. The example shown in Fig. 26A and B shows bedding disaggregation leading to balling of coarser material in a liquified matrix. The walls of this pit also show several fissures which have been subsequently filled with material from above (Fig. 27). Strata adjacent to the fissures show marked downwarping towards the fissures which are similar to some of the cryogenic fissures described by French and Gozdzik (1988) from Belchatow, Poland.

4.6.4. The folds, faults, flame structures and structures related to liquifaction and bedding disaggregation described from site 5, are largely restricted to the lower sand and pebbly sand sequence at, or just below, the upper silt and clayey-silt sequence. In some places the contact between the lower and upper sequences is a clear unconformity. Thus, the observed deformation must have taken place at or close to the free surface of the sediments. The deformations are commonly localized on flanks of gentle synformal structures which, as mentioned earlier, are probably syndepositional features in channel-fill deposits. It appears that prior to the deposition of the upper sequence, the lower sequence was exposed to subareal processes and was cut by numerous shallow channels.

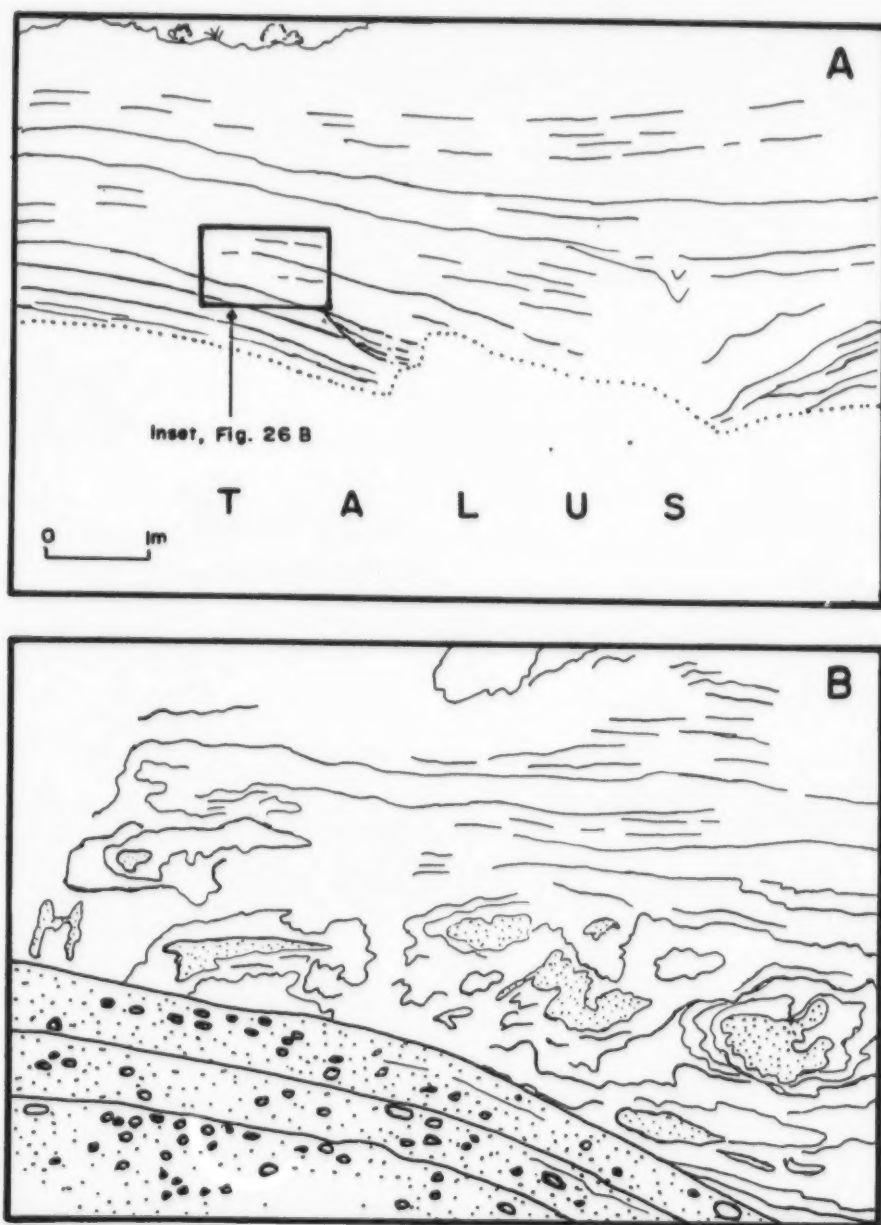


Fig. 26 A & B. Bedding disaggregation leading to balling of coarser material at site 5.

The gravitational instability occurred in the sediments on the flanks of these channels. Seismic shaking is an effective trigger for this type of instability although other mechanisms are possible. Because of the extreme lateral variability of these deposits, it was not possible to establish whether the deformations observed in various cuts were synchronous.

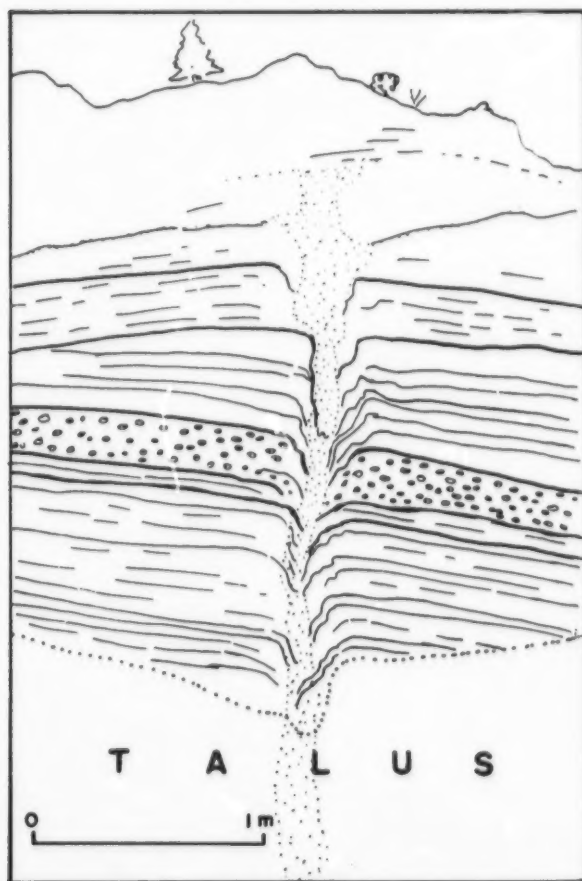


Fig. 27. Probable cryogenic fissure filled with silt from above, from site 5.

4.7: Site 6, Bocabec River (NTS 21G/2; for location see Figs. 4 and 28)

This site is on the east side of Bocabec River and can be reached via a gravel road leading south from Highway 127. The numerous shallow gravel pits which occur in an area of about 250m x 1000m are located on the NNE trending Bocabec esker (Finamore and Seaman, 1988). The pits have been inactive for sometime and their walls are largely talus covered. However, because Finamore and Seaman (1988) have mentioned the presence of glaciotectionic structures on the flanks of the Bocabec esker, pit walls at 11 selected points were partially cleared of talus. Only one of them showed interesting deformation.

The northeast face of a cut in the northern part of the pit complex showed a disturbed (folded) horizon of thinly laminated clay (varved clay), about 0.6 m thick (Fig. 29). Judging from the lack of microfaults in the section, the smoothness of the folds and the thickness variations shown by individual laminae, it appears that the deformed sediments were either in a liquid or hydroplastic state. The folds strengthen upwards (possibly from an undeformed base although this could not be verified with certainty) and die away towards the top. Since the folds consistently lean southeast i.e. towards the Bocabec River, a downslope force component was probably operative. Ice drag, or more likely the downslope slip of the overlying sediment mass, may have produced the deformation.

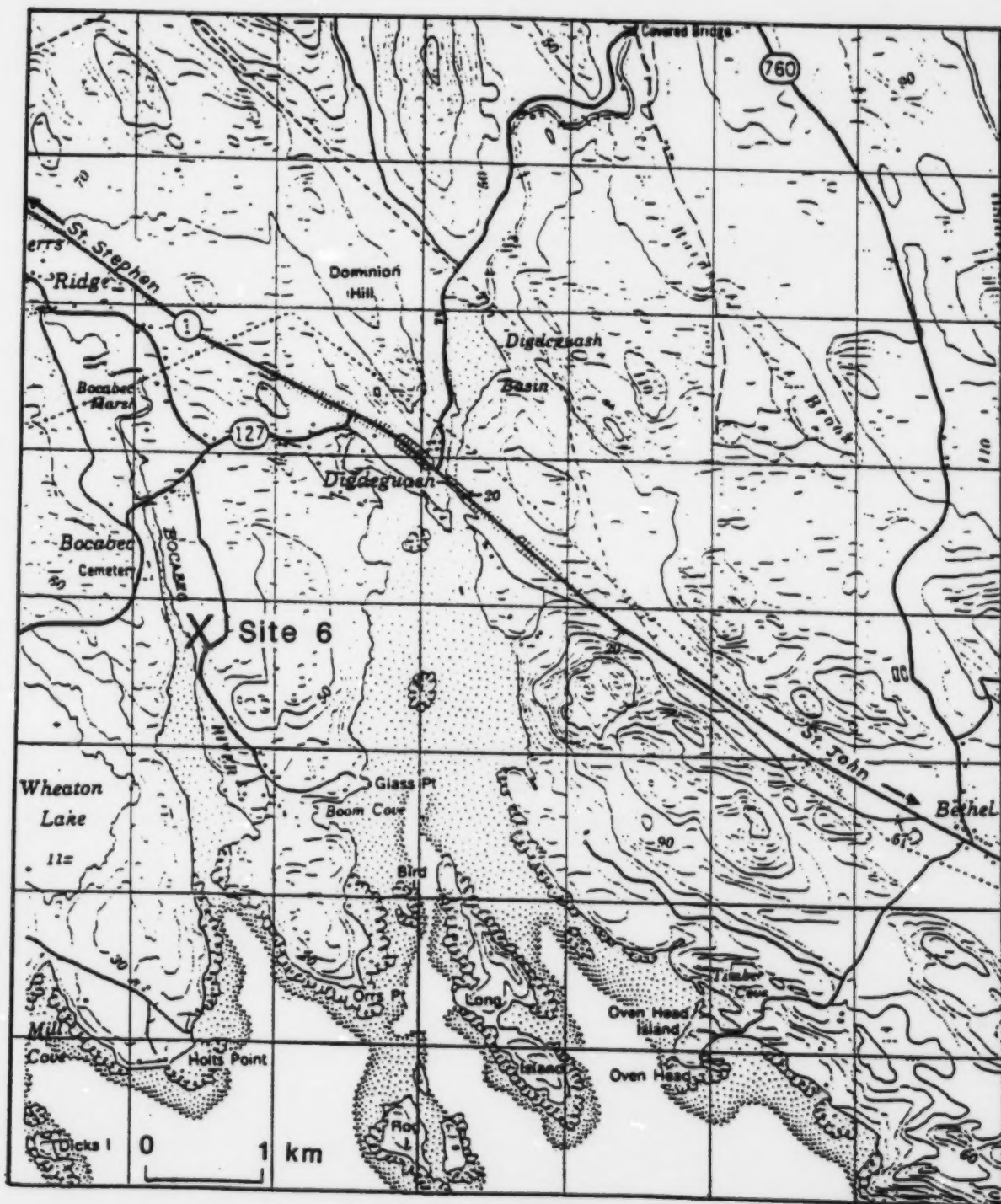


Fig. 28 Location: site 6, Bocabec River. Base map from 21G/2. Department of Energy, Mines and Resources, Canada.

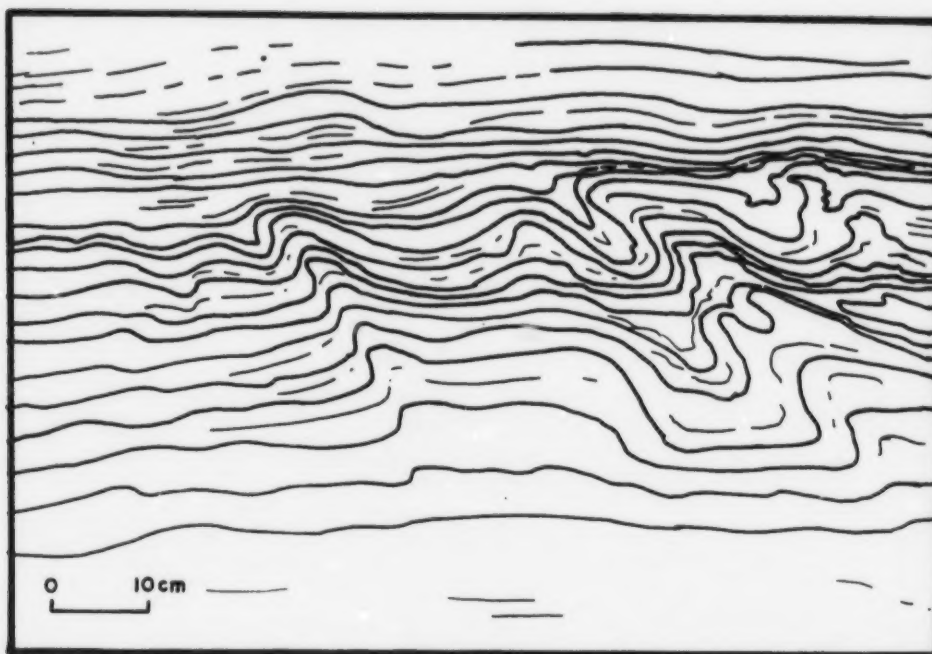


Fig. 29. Disturbed horizon in thinly laminated clay at site 6. Location of site shown in Fig. 28.

4.8. Site 7, Sandy Point, St. Croix River (NTS 21G/3, for location see Figs. 4 and 30)

This site, on the east bank of St. Croix River, is close to the Oak Bay fault and can be reached from Highway 127 through a privately owned trailer park. The site has several sand-gravel pits, some of which were active on a small scale. In the summer of 1987, the cuts at the site are known to have exposed several faulted sections (Art Ruitenberg, personal communication). However, despite careful search these sections were not found. It appears that they have since been mined.



Fig. 30. Location of site 7, Sandy Point, St. Croix River. Base maps from 21G/3, Department of Energy, Mines and Resources, Canada.

A fresh cut into a steep cliff on the bank of St. Croix River, exposed a well-stratified sequence of sand and silt cut by a single fault (Fig. 31), strike 120° and dip 60° SW. The faulted beds cannot be matched across the fault but show pronounced drag which is consistent with normal faulting, the slip being towards the river. The fault probably represents a slump surface.



Fig. 31. Fault probably representing a slump surface in a sand and silt sequence at site 7. For location see Fig. 30.

4.9 Site 8 St. Stephen (NTS 21G/3, for location see Figs. 4 and 32)

This site is approximately 4 km north of St. Stephen and can be reached via a gravel road from Highway 750. The sand and gravel pit at the site was active with crushing and screening operations; several inactive pits occur close by. Thibault (1982) examined the site in 1981 and reported the occurrence of faulted beds. Several faulted sections were exposed at the time the site was visited in August 1988. Their locations are shown on Figure 33.

4.9.1 Sections A and B, Fig. 33.

These two sections are best described together because they represent parts of a single structure, the substructure of a kettle exposed on the walls (maximum height 7m) of a crescent-shaped (convex to the west) cut. Mining has destroyed a part of the kettle, but what remains of the vestige of its morphology, clearly defines a shallow bowl-shaped depression. Section A (Fig. 34) shows a lower, sub-horizontal sequence of alternating beds of sand and clayey sand, truncated by a curved (concave upwards) unconformity, representing a part of the kettle floor essentially in its initial form. Overlying the unconformity is a weakly-bedded wedge (thickening towards the centre of the kettle) of sand with local gravel horizons representing the kettle fill. Numerous faults occur on both sections (Figs. 34,35). They downdrop the lower sequence progressively towards the centre of the kettle.

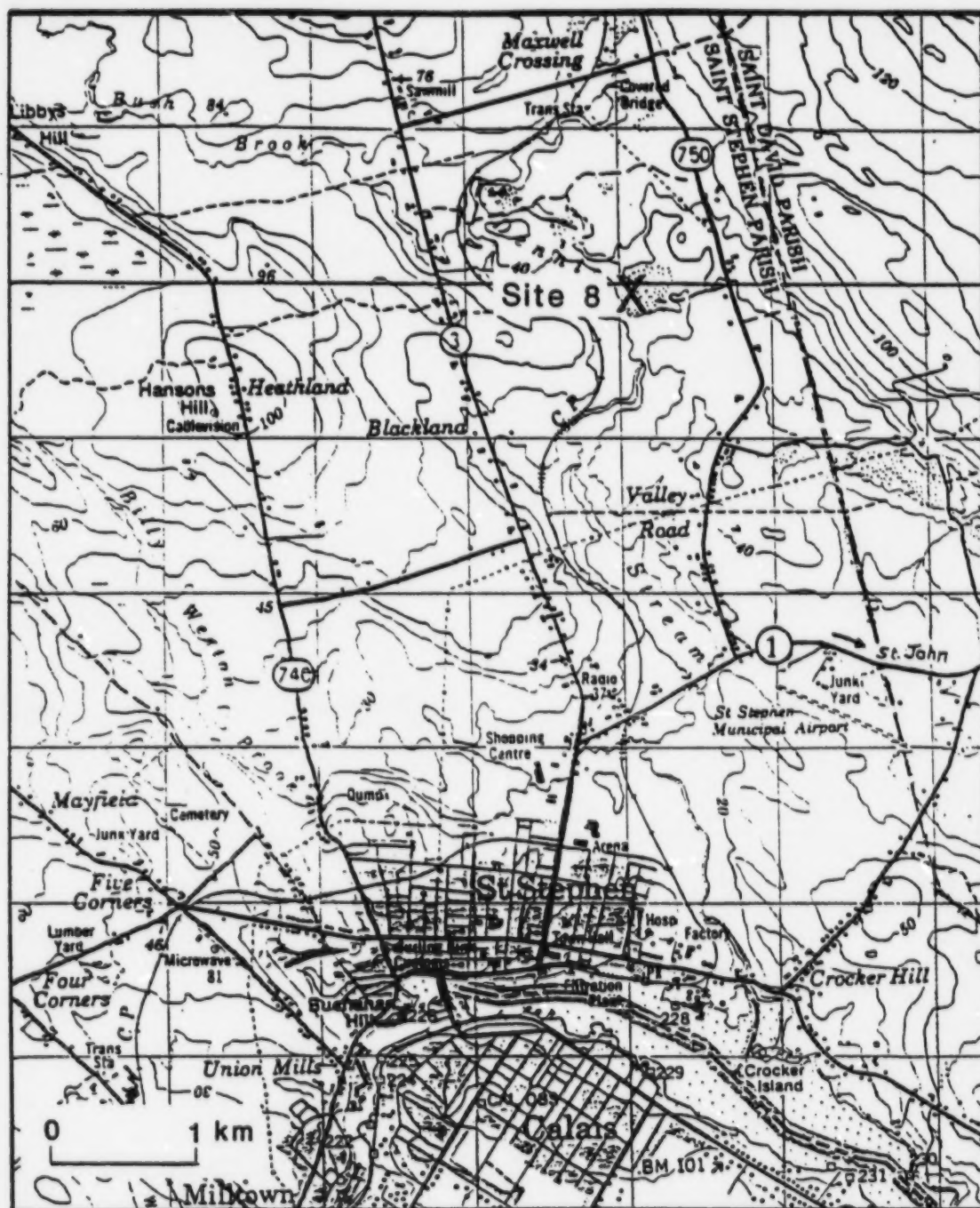


Fig. 32. Location: ste 8. Base map from 21G/2. Department of Energy, Mines and Resources, Canada.

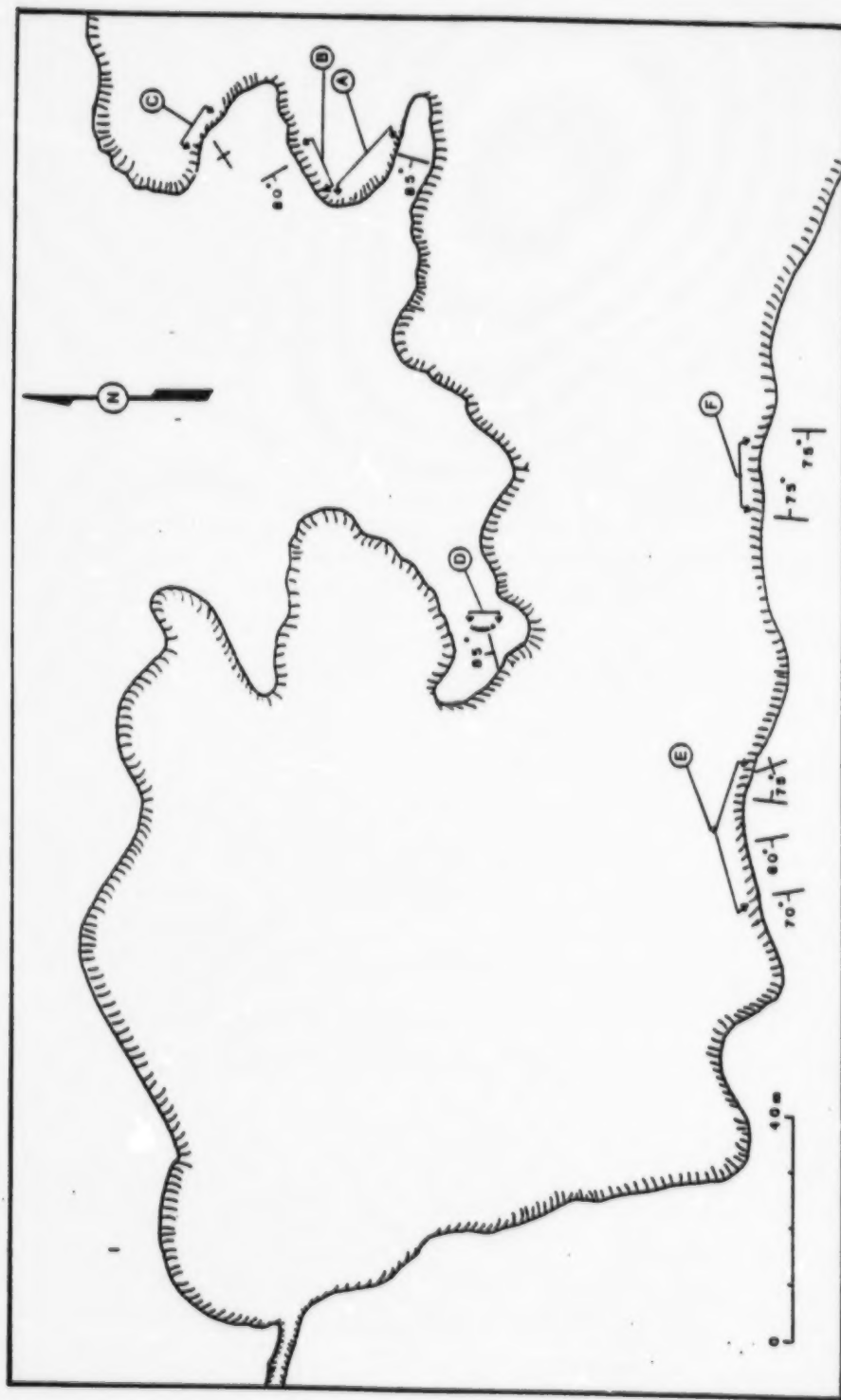


Fig. 33. Sketch map of the sand-gravel pit at site 8 showing the locations of sections A to F, shown in detail in Figs. 34 to 41. Symbols represent generalized strike and dip directions of faults. For location of site 8, see Fig. 32.

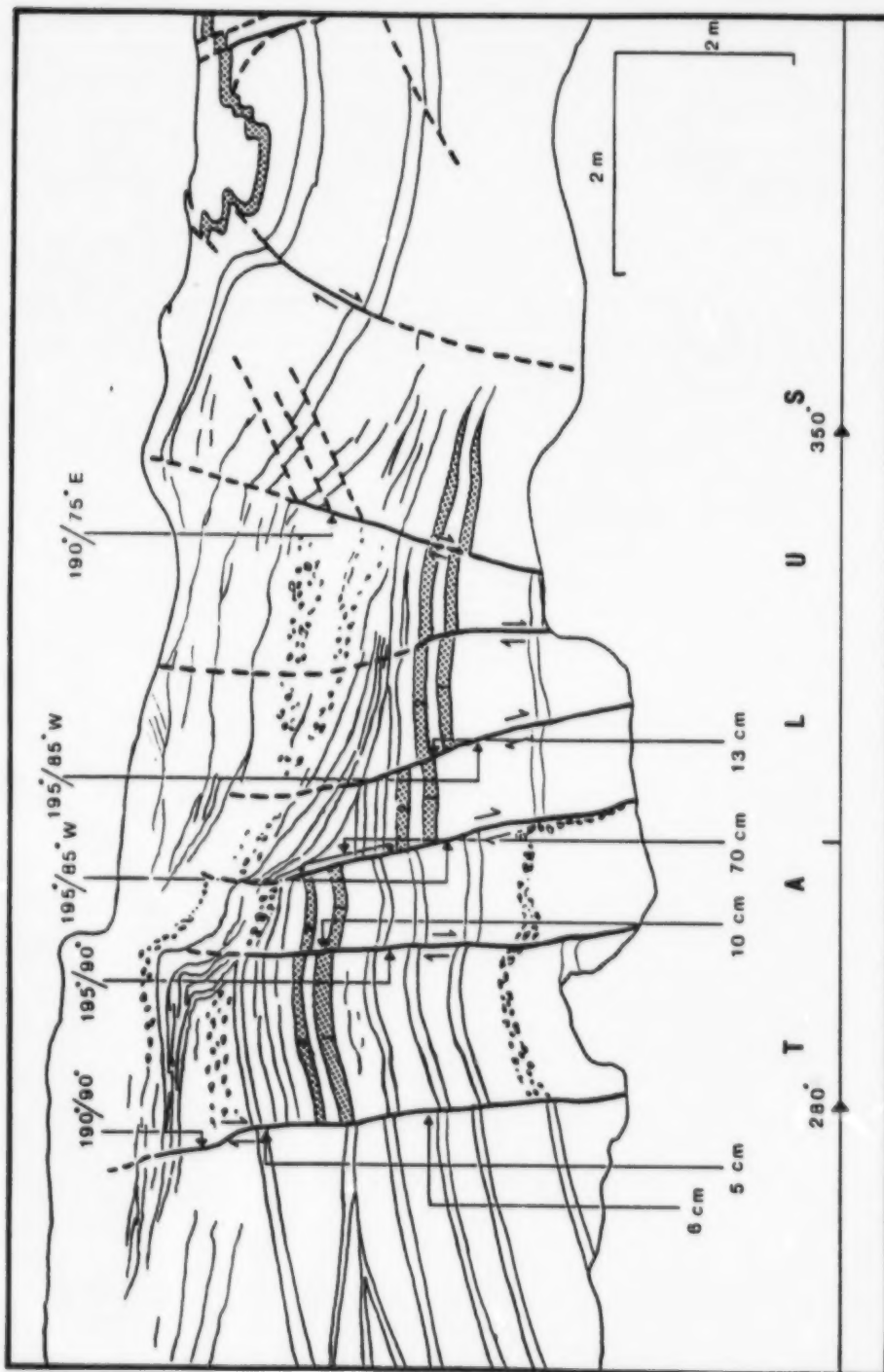


Fig. 34. Details of section A, site 8. The faults (thick lines) are structural elements of a kettle. The deformed beds at the upper right corner of the section are at the centre of the kettle. For location of the section see Fig. 33. The numbers (in degrees) given at the top are strikes and dips of faults. Those (in centimetres) at the bottom of the frame are the measured amounts of displacements on faults.

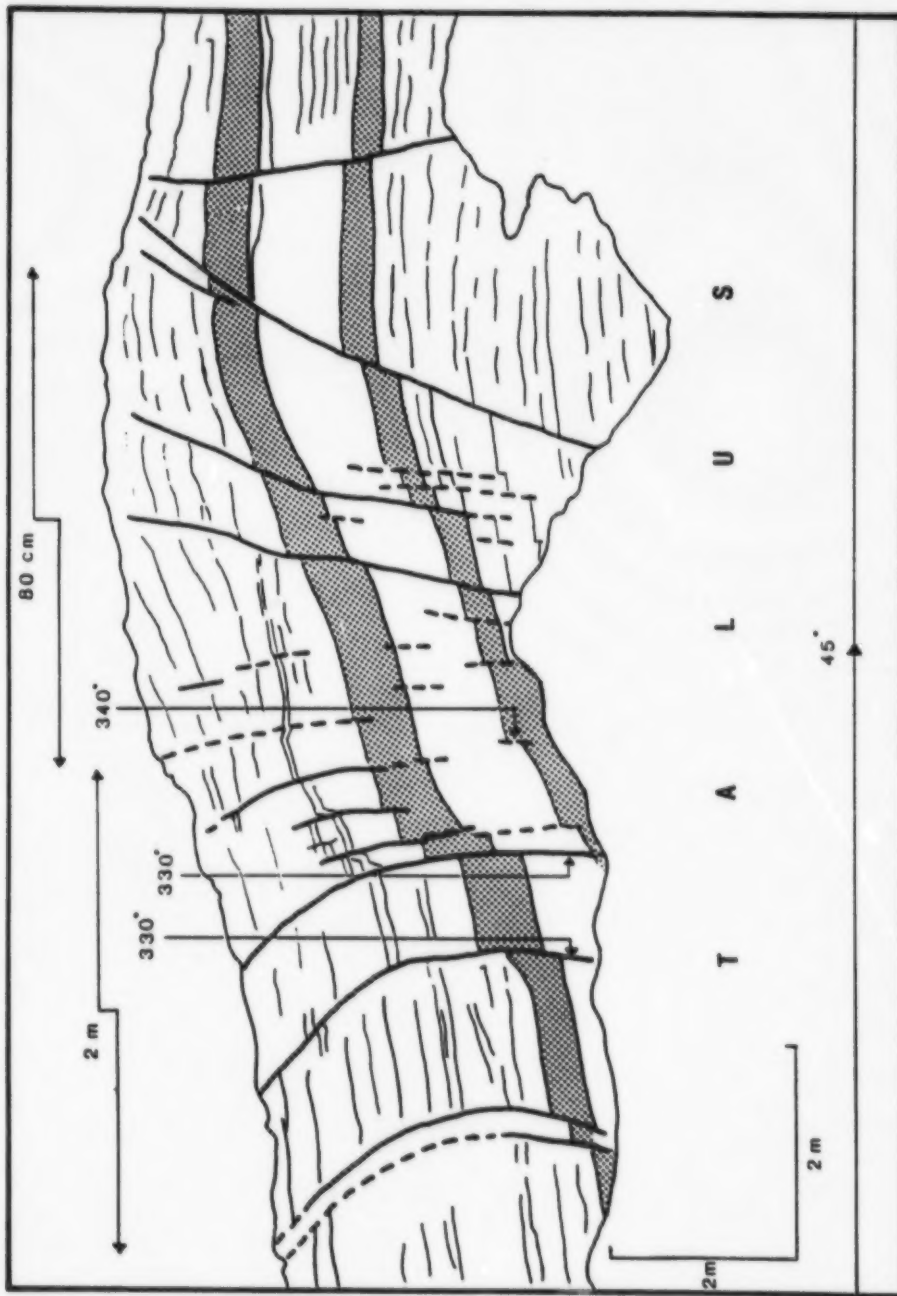


Fig. 35. Section B at site 8. Location of section shown in Fig. 33. The faults (thick lines) of this section and those of section A (Fig. 34) are structural elements of the same kettle. The numbers (in degrees) at the top are strike directions of vertical faults. The stepped lines at the top show the cumulative displacement on faults for the corresponding spans of the section.

Those in the central part of the kettle are curved (convex upwards) high-angle reverse faults that dip away from the centre of the kettle. Outside this reversely faulted central block, faults are either vertical or dip steeply towards the centre of the kettle (i.e. normal faults). In plan, the fault traces are circular arcs, disposed concentrically with respect to the kettle's centre. The sediments in the central part of the kettle are folded (Fig. 34), probably as a result of gravity induced slippage. Although the faults can be traced into the sediment fill, they have only minor (few centimetres) displacements and they invariably die out in this sequence. Evidently, faulting created the kettle, essentially in its initial form, but minor fault movements took place during sedimentation. The similarity of the fault to Sandford's (1959) type II experimental fault pattern is striking except that the normal faults of the former are far more strongly developed than those of the latter. The interpretation is that a block of ice about 3 m thick melted to create the kettle.

4.9.2. Section C, Fig. 33.

This section (Figs. 36, 37) exposed on a cut about 8.5 m high, shows a faulted sequence of thinly-bedded sand containing a few thicker interbeds of poorly sorted pebbly sand. Although faults affect an approximately 10 m section, most of them are concentrated in a 4 m wide zone and systematically downdrop the beds to the northwest (right in Fig. 36). At the base of the section, the faults are essentially vertical and strike 225° to 240° . Upsection

they curve to form steeply dipping (to the southwest) high-angle reverse faults. The fault pattern is similar to the pattern on one edge (left edge in Fig. 6B) of Sandford's (1959) model II experiment suggesting that the fault pattern is related to melting of a buried mass of ice.

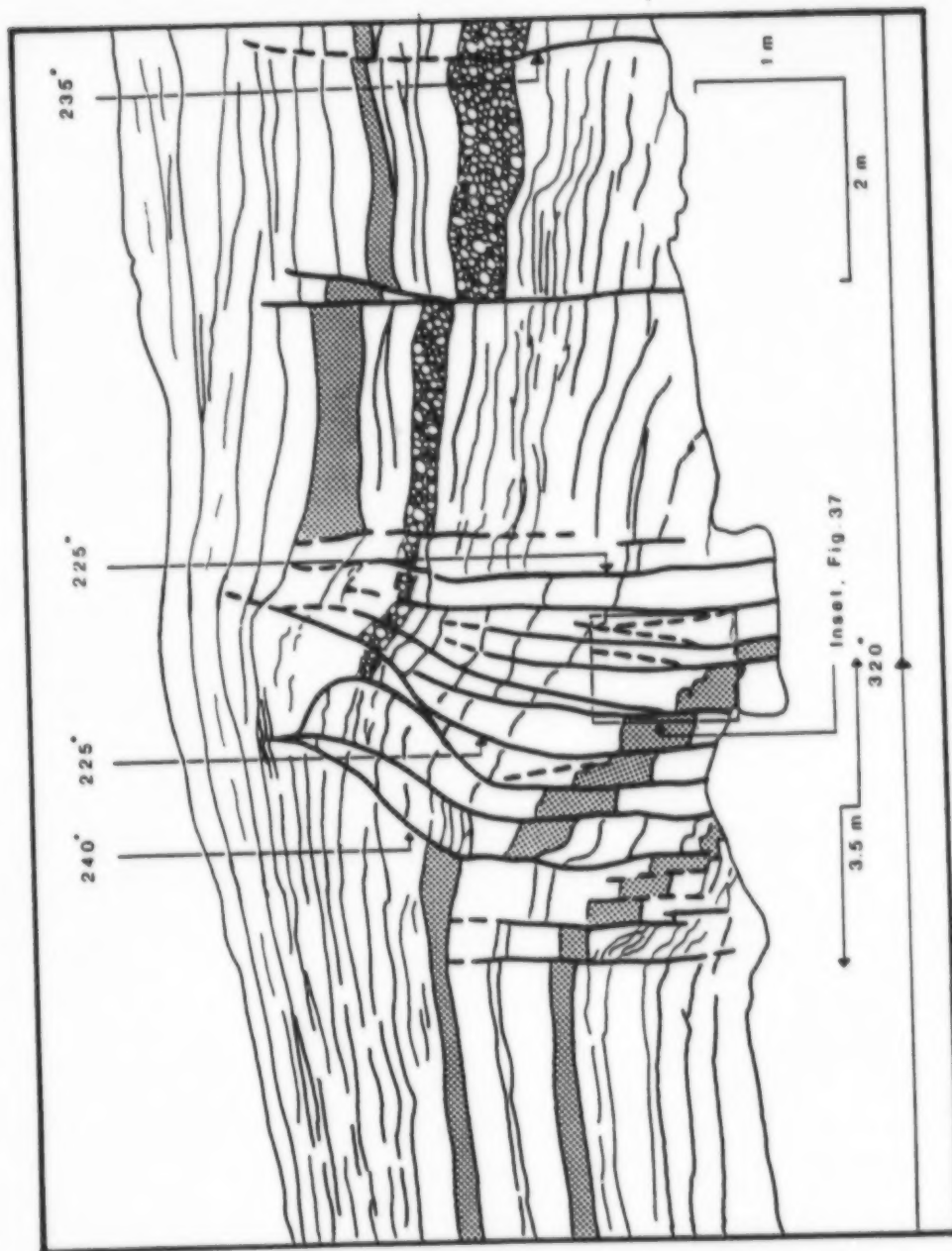


Fig. 36. Section C at site 8. For location of section see Fig. 33. Faults: Thick lines. The stepped line at bottom shows the cumulative displacement on faults of the corresponding span of section.

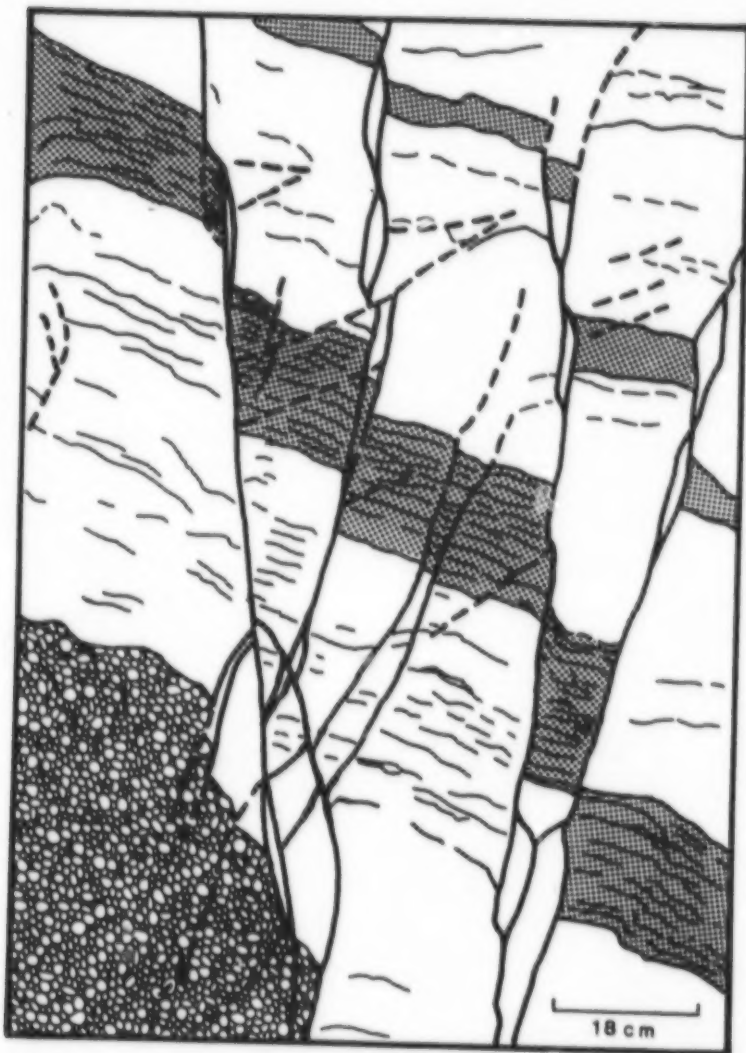


Fig. 37.
Detailed fault
pattern of a part
of section C,
site 8. For
location see Fig.
36.

4.9.3. Section D, Fig. 33.

The sandy beds of this section, 1.6 m high are cut by a fault zone about 2.5 m wide (Fig. 38), consisting predominatly of NW dipping high-angle (75° to near vertical) normal faults, striking at 245°

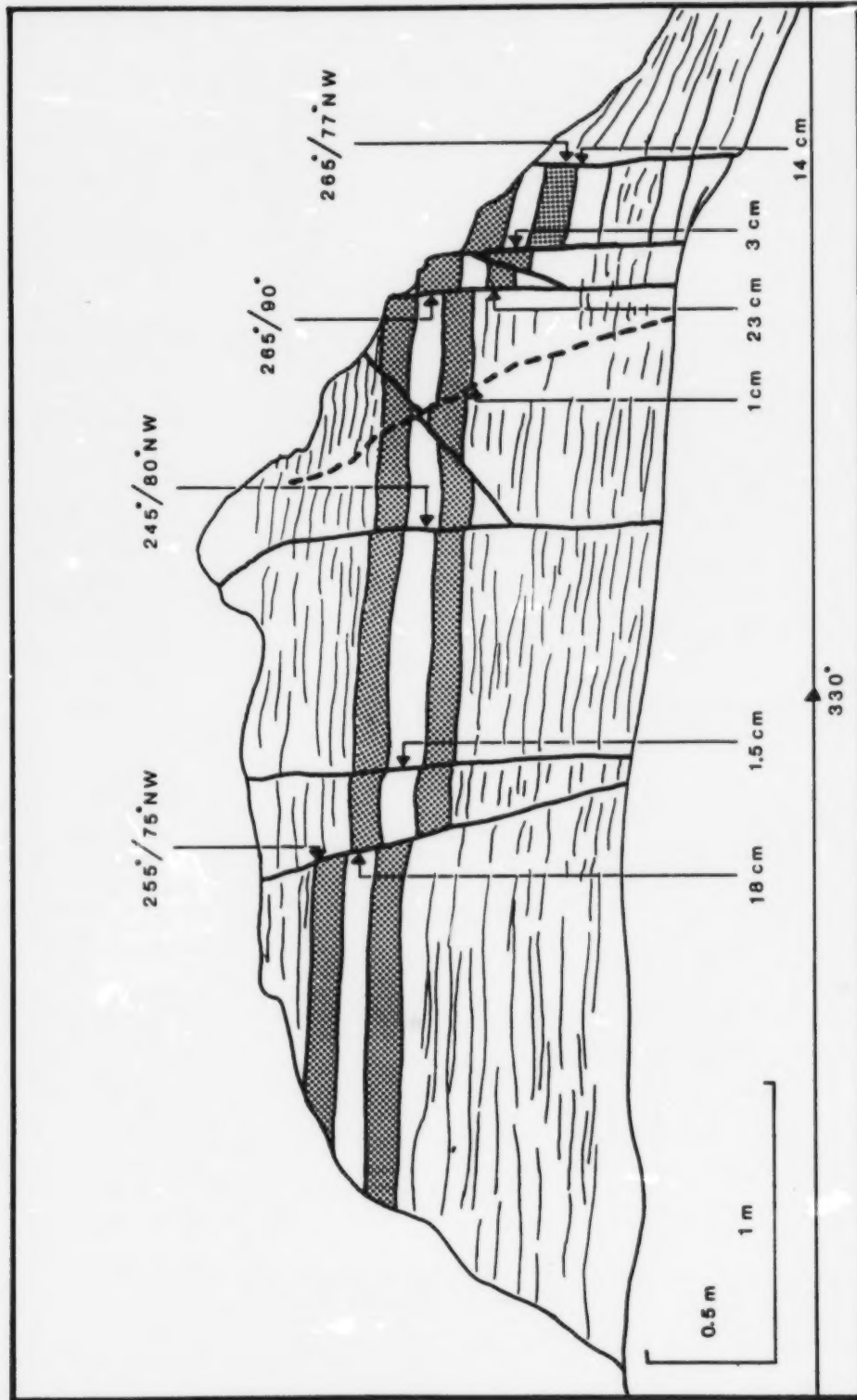


Fig. 38. Section D at site 8. For location see Fig. 33.

to 265° . The cumulative displacement is less than 1 m. Interest in this section arose from the possibility that it may be the continuation of the fault of section C. However, careful examination of the area between the two sections provided no evidence for a continuous fault zone. On the contrary faults of section C, instead of keeping a straight course towards section D, curve sharply to the right to form circular arcs (in plan) about a centre located in the excavated embayment of the pit to the north of section C (see Fig. 33). Such a pattern is consistent with the proposed origin of these faults by melting of buried ice.

The origin of faults in section D is not clear. The fact that they were not visible on a cut just 10 m away suggests that they either curve sharply or that they die out within a very short distance. The preferred interpretation is that these faults are also related to loss of support due to melting of buried ice, the main reason for this preference being their close association with faults formed by this mechanism.

4.9.4 Section E and F, Fig. 33

These sections are from a relatively straight segment of the southwall of the pit. Microfaults are present throughout this segment of the pit-wall but larger faults are concentrated in sections E and F (Figs. 39,40,41). A prominent feature of these latter faults is the presence of silt infillings, up to 15 cm thick. Section E (Fig 39), approximately 26 m long and up to 7 m high, shows a sequence of stratified gravelly and sandy sediments

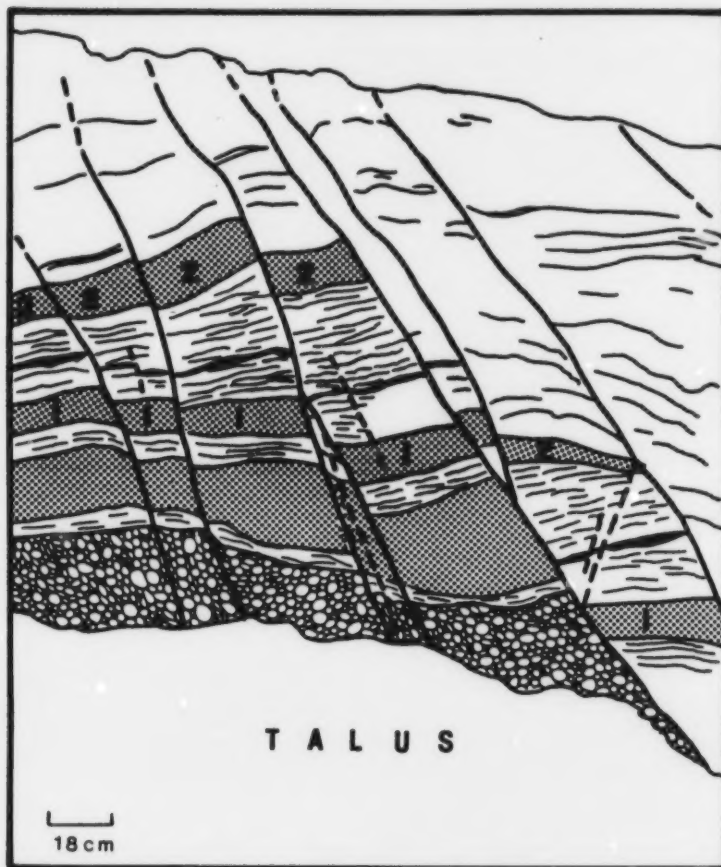


Fig. 40. Detailed fault pattern of a part of section E, site 8. For location see Fig. 39.

which at one end (right in Fig. 39) of the section are unconformably overlain by a westward thickening wedge of weakly-bedded, poorly-sorted sand, and pebbly to cobbly gravel. The central part of the section consists of a structural high from which the beds are successively downfaulted towards each end of the section. On the west flank of the structural high, the cumulative downthrow exceeds 6m and on the east flank it exceeds 4m. The faults west of the structural axis are N to NNW trending normal faults with westerly dips ranging from 60° to 70° . Strike

directions of faults on the east side of the structural axis vary from 115° to 210° but the majority of them strike NNW to NW. Those faults near the structural axis (on the east flank of the structural high) are easterly dipping ($\sim 85^{\circ}$) normal faults, but further away from the axis faults generally tend to be vertical in the lower part of the section and curved in the upper part with no apparently preferred sense to their curvature.

Faults similar to those of section E have been described by McDonald and Shilts (1975) from ice front fans or beads of the Windsor esker, Quebec. Major normal faults occur near the crests of beads and strike parallel to the esker trend.

The question whether the sand and gravel deposits at site 8 represent an ice front fan needs investigation. However, their overall characteristics are consistent with deposits formed in an ice proximal environment. The presence of at least one clearly identifiable kettle supports this view. The predominant trend of faults in section E is NW to NNW which is broadly parallel to the ice flow direction in the general area (Rampton et al., 1984) and hence to the trend of possible eskers.

Normal faults in an ice front fan are thought to form as a result of melting of a saucer-shaped ice base remaining after the upper part of the related ice tunnel has wasted (McDonald and Shilts, 1975). A similar mechanism may be applicable to the faults of section E.

The predominantly sandy beds of section F (Fig. 41), about 14 m long and up to 6 m high, are cut by approximately north trending normal faults to produce a shallow (< 1 m) graben. This structure is not present on the opposite wall of the pit which is only 50 m away. Its close association with structures resulting from ice melting suggests that this structure may also be related to the same process. The fault pattern of Sandford's (1959) model II experiment shows that small graben structures could form peripheral to the main collapse structure.

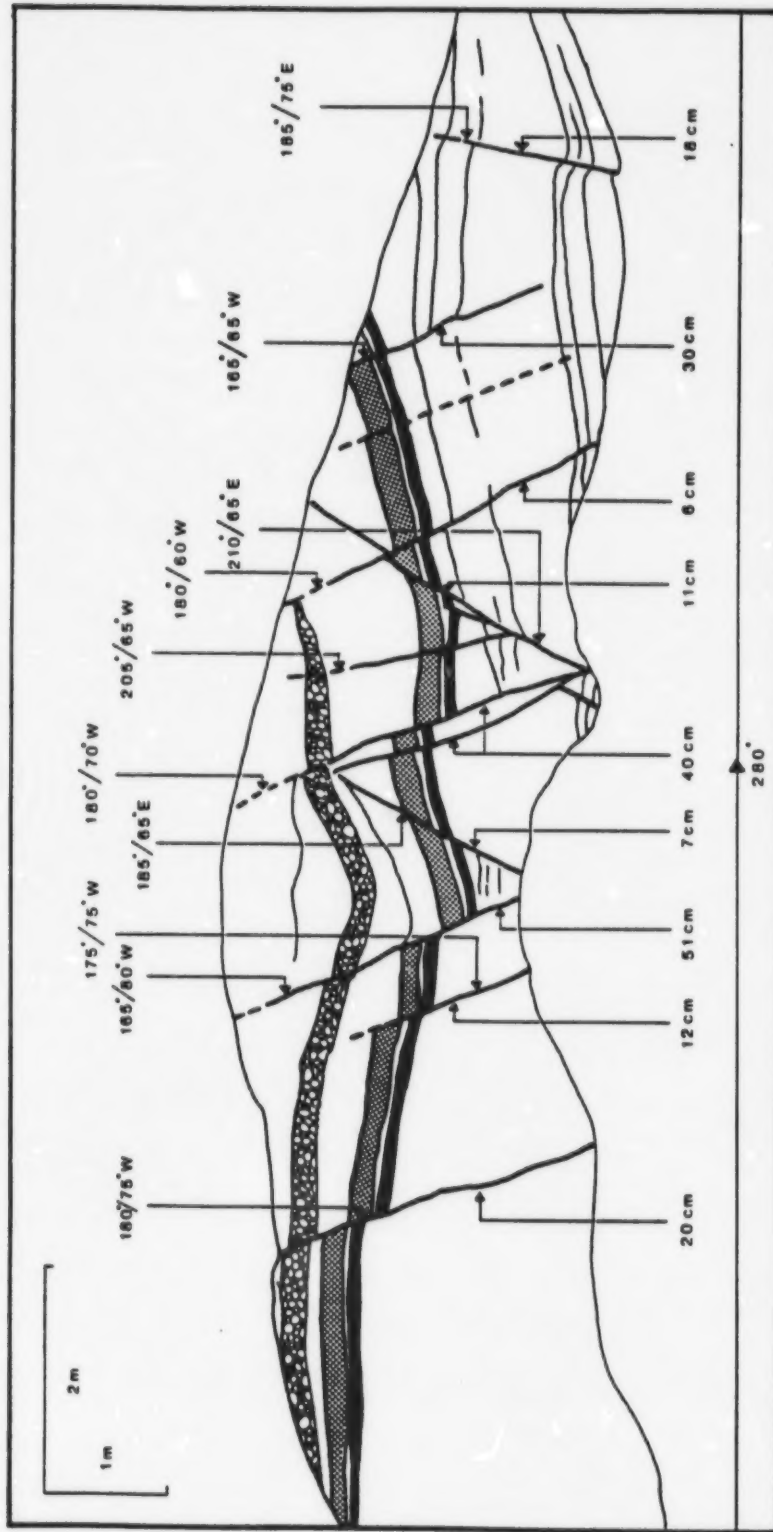


Fig. 41. Section F at site 8. For location see Fig. 33.

5. DISCUSSION AND CONCLUSIONS

The various structures described from the eight sites, with exception of probable cryogenic fissures at Site 5, can be classified on the basis of their origin into two groups: (i) collapse structures due to loss of support created by melting of ice masses, and (ii) structures related to downslope or downdip movement of sediment masses. Those of the first group are the most prominent post-depositional structures in the glacial sediments of the Passamaquoddy Bay area. However, because they have no bearing on the seismicity of the region, they will not be discussed further.

The second group of structures (found at sites 2 and 5) require the action of a mechanism to reduce sediment strength and a driving force to cause deformation, although under certain circumstances sand will behave as a cohesive substance (e.g. frozen sand, sand which is damp but not saturated) and may deform by brittle failure or plastic flow (Owen, 1987). Reduction of sediment strength can be effectively achieved by seismic shaking. The principal driving force is, of course, the gravitational body force.

Several authors (e.g. Allen and Banks, 1972) have pointed out that liquefaction, induced by earthquake ground motion, is an effective way of deforming sediments close to the contemporary sediment surface. Seilacher (1984) has referred to sediments containing seismically-induced structures as "seismites" and has focused

attention on the considerable difficulties in unambiguously identifying ancient seismites. A major problem is that there are many potentially unstable slopes which originate as depositional or erosional surfaces. In the ice contact depositional environment, loss of lateral support of sediments also occurs due to melting of ice walls. Failure of such slopes under non-seismic stresses produce structures identical to those induced by seismic shaking. Although large dewatering pipes are characteristic of sediments which have undergone strong seismic shaking, they are not unique to this environment (Leeder, 1987).

Identification of ancient seismites in glaciofluvial and ice contact deposits presents a special problem. Since seismic shaking is the most effective, regionally extensive trigger, deformed soft sediments spread over a wide area (size of area dependent on the magnitude of the event) and restricted to an "instant" time window would favour their identification as seismites. Although the establishment of such criteria may be possible, for example in the case of extensive lake deposits, it is difficult to do so in patchy, highly variable deposits such as the glacial deposits in Passamaquoddy Bay area.

It is quite unlikely that the faults in glacial sediments described from the various sites are upward continuations of bedrock faults. The latter faults usually have very small (a few mm) post-glacial displacements and it is highly improbable that such small

displacements could be propagated through thickness of unconsolidated sediments, let alone producing the relatively large (up to a few metres) fault displacements observed in these sediments.

In summary, because earthquakes of $M \geq 5$ have occurred in the study area, the possibility that some of the deformed glacial deposits described in this report, especially those resulting from slope failure, are seismites cannot be ruled out. However, a unique interpretation of the causes which led to slope instability in these cases is difficult if not impossible.

6. ACKNOWLEDGEMENTS

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